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TESTS IN THE NACA TWO-DIMENSIONAL LOW-TURBULENCE TUNNEL OF AIRFOIL SECTIONS DESIGNED TO HAVE SMALL PITCHING MOMENTS AND HIGH LIFT-DRAG RATIOS

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SUMMARY

Airfoil sections that have small or zero pitching-moment coefficients and high lift-drag ratios have been developed and tested. With sections having pitching-moment coefficients close to zero, maximum section lift-drag ratios that were almost twice as great as those which have been attained on sections of the NACA 230-series airfoils were attained in the Reynolds number range from 1.7×10^6 to 3.2×10^6. Such characteristics are desirable for rotor-blade sections, but the new sections have the disadvantage that they are unduly sensitive to roughness. The action of forces caused by the rotation of the blades on the partly stalled regions over the rear portion of the airfoils in the rough condition is not well understood, but it is believed that the action may be beneficial. It is felt desirable that some of the new sections be tested in a full-scale rotor.

INTRODUCTION

Two of the most important characteristics of airfoil sections designed for use on rotor blades are low profile-drag coefficients in the useful range of lift coefficients and practically zero pitching moment about the aerodynamic center. The purpose of the present investigation was to develop airfoils with zero pitching moment that, at high lift coefficients, had profile-drag coefficients no larger than those usually obtained with low-drag airfoils at low lift coefficients. The maximum lift-drag ratio $(c_l/c_d)_{max}$ was used as a criterion of the airfoils. The use of $(c_l/c_d)_{max}$ as a criterion favors the airfoil that can maintain low drag at high lift coefficients over the airfoil that has equal or possibly lower drags at smaller lift coefficients. This criterion, in effect, places most importance on the reduction of rotor profile power in the hovering range and at low forward speeds. As the forward speed increases, the airfoils operate over a much wider range of lift coefficients; and, although low profile drags are still desirable, the simple criterion $(c_l/c_d)_{max}$ in itself no longer provides sufficient basis for choice of an airfoil.

Of the conventional airfoil sections previously developed by the NACA, the NACA 230 series gave the highest lift-drag ratios with small pitching moments. It seemed likely that lift-drag ratios higher than obtained with the NACA 230-series airfoils could be attained, while zero pitching moment was maintained, by designing the airfoils to keep extensive laminar boundary layers in the design range of lift coefficients. A series of sections were accordingly designed and tested in an attempt to obtain the highest lift-drag ratios with zero pitching moment.

Two groups of new airfoils and one member of the NACA 230 series were tested. The first group of new airfoils consisted of a low-drag airfoil and modifications of it. The original airfoil of this group had a high lift-drag ratio but a pitching moment too large for use on rotor blades. Several modifications of the tail portion of this airfoil were made in an attempt to reduce the pitching moment and, at the same time, to maintain lift-drag ratios as high as possible. The second group included two low-drag airfoils that differed only in the amount of camber. The NACA 23015 airfoil section was tested at the same Reynolds number as the newly developed sections and the data are included for comparison.

APPARATUS AND METHOD

The tests of the new airfoils were made in the NACA two-dimensional low-turbulence tunnel, hereinafter designated NACA LTT. This tunnel has a test section of the same dimensions as the test section of the NACA two-dimensional low-turbulence pressure tunnel, hereinafter designated NACA TDT, which is described in reference 1, but operates only at atmospheric pressure. The lift and drag of a model are obtained by the same method as in the

NACA TDT (reference 1). The pressure distributions on the models were obtained by using a small static-pressure tube that could be placed at the desired position on the airfoil surface. The pitching moments were measured in the NACA LTT by so mounting the models that they were free to pivot in a ball bearing located in one wall of the tunnel and restrained through the other wall by a torque arm consisting of a calibrated steel rod acting in torsion. In order to allow the model to pivot on the torque arm, it was necessary to leave small gaps between the model ends and the tunnel walls. The effects of these end gaps on the measured lift and drag were eliminated by retesting the models sealed to the walls. The lift and drag data presented were obtained with the models sealed to the tunnel walls for all models except the NACA 2-H-15 airfoil section. The data for this model were believed to be sufficiently reliable as obtained to make a special test unnecessary. The effect of the end gaps on the pitching moments is believed to be small especially because, throughout their useful range, the airfoils had pitching moments that were practically constant. All the data have been corrected for the finite size of the test section.

The NACA 23015 airfoil section was tested in the NACA TDT. The methods of obtaining lift and drag are explained in reference 1. In order to obtain pitching-moment data, a torque arm fastened to the model is used. The torque arm used in the NACA TDT is much stiffer than the torque arm used in the NACA LTT and, in addition, the torque arm in the NACA TDT incorporates a damping device.

The method of constructing and finishing the models is explained in reference 1. Two groups of new airfoils, including the models designated NACA 1-H-15, NACA 2-H-15, NACA 3-H-13.5, NACA 4-H-12.4, NACA 5-H-15, and NACA 6-H-15 and one member of the NACA 230 series, the NACA 23015, were tested. The designations of the newly developed airfoils are considered temporary pending the development of a more descriptive system of designation. The first number is merely a serial number to identify the airfoil. The H means that the airfoils were developed for use on rotating-wing aircraft. The last two numbers give the thickness ratio of the airfoil t/c in percentage of the chord.

In figure 1 are presented plots of the airfoils and in table I, the ordinates for the airfoil sections. The NACA 1-H-15 airfoil was the original low-drag section used in the derivation of the NACA 2-H-15, NACA 3-H-13.5, and NACA 4-H-12.4 airfoil sections. In order to reduce the pitching moment, the tail was swept up resulting in the NACA 2-H-15 airfoil section. The pitching moment was still high. A tail extension was therefore added and the upsweep at the tail was slightly changed resulting in the NACA 3-H-13.5 airfoil section. Finally, in an effort to increase $(c_l/c_d)_{max}$ the upsweep at the tail was removed and a longer tail extension was used resulting in the NACA 4-H-12.4 airfoil section. The NACA 5-H-15 and 6-H-15 airfoils have the same thickness distribution and the same type of mean line but the NACA 6-H-15 has 35 percent more camber than the NACA 5-H-15 airfoil.

PRESENTATION OF RESULTS

The results of the tests are presented in figures 2 to 22. A lift-drag polar is given for each airfoil. Section lift coefficient c_l and section pitching-moment coefficient about the aerodynamic center $c_{m_{a.c.}}$ are plotted against the section angle of attack α_0. A pressure-distribution curve of $\left(\frac{U}{U_0}\right)^2$ against x/c is given for each of the new airfoils at approximately the design angle of attack; $\left(\frac{U}{U_0}\right)^2$ is the square of the ratio of the local velocity over the airfoil surface to the undisturbed velocity of the stream; x/c defines the position along the airfoil chord and varies from zero at the nose to unity at the tail. In figure 22 is presented a lift-drag polar for the NACA 5-H-15 airfoil section with the nose roughened. The characteristics of the various airfoil sections are summarized in table II.

DISCUSSION

The relative importance of various desirable airfoil characteristics depends in large measure on the requirements of the particular design. It appears necessary, however, that any section to be used on rotating-wing aircraft have zero, or at least very small, pitching moment. Low profile drags are desirable but the profile drag cannot always be reduced in one range of lift coefficients without increasing the profile drag in another range. The particular range of lift coefficients in which low profile drags are most important depends on the requirements of the specific design. High values of $(c_l/c_d)_{max}$ are particularly desirable for helicopters in the hovering condition and at low forward speeds. The significance of this criterion in itself decreases as the forward speed of the aircraft increases because the range of angles of attack through which the blade section operates increases. The importance of high critical Mach numbers increases as the forward speed of rotating-wing aircraft increases. The importance of high maximum lift coefficients also increases with the forward speed of the aircraft.

In designing the airfoil sections, most emphasis was put on obtaining high lift-drag ratios with zero pitching moments. Sections that had high lift-drag ratios also had low profile-drag coefficients and relatively high critical Mach numbers at fairly high lift coefficients. The emphasis on aerodynamic requirements produced airfoils that had concave curvature at the rear upper surface. Although to some users of the airfoils the concave curvature may appear undesirable from constructional considerations, the present methods of construction may possibly be so modified that full advantage may be taken of the aerodynamic characteristics of the airfoils without paying too high a price in weight or difficulty of construction.

Some of the new airfoils have pitching moments practically equal to zero throughout the useful range of lift coefficients. It is difficult, however, to combine zero pitching moment with the high design lift coefficients necessary for high lift-drag ratios because, for zero pitching moment, the forward portion of the airfoil carries more lift at a given lift coefficient than it would if there were no down load at the rear of the airfoil. The boundary layer over the upper surface of a zero-moment airfoil is thus closer to separation at a given lift coefficient than is usual for a cambered airfoil with the lift spread more evenly over the chord. In addition, because the lift is unevenly distributed over the chord, the critical Mach number at the design lift coefficient is lower for the new airfoils than it would be if some pitching moment were permitted.

Over fairly large ranges of the lift coefficient, the new airfoils, in their smooth condition, have drags that are appreciably lower than the drags obtained with the best of the previously developed NACA conventional airfoil sections having a surface finished in the same manner as the low-drag sections. Lift-drag ratios almost twice as large as can be obtained in the same Reynolds number range with the best of the previously developed conventional airfoil sections have been obtained with the new low-drag sections. Outside this low-drag range, however, the new airfoils have higher drags than conventional airfoil sections.

The critical Mach numbers of the new airfoils, given in table II, have been estimated from the pressure distributions given in the figures. Within and above the low-drag range, the critical Mach numbers of the airfoils will decrease with increase of lift coefficient. If the lift coefficient is decreased much below the value at the low-lift end of the low-drag range, a peak that will cause a reduction in the critical Mach number will occur in the pressure distribution at the nose of the airfoil on the lower surface. The new airfoils, which have the lift more evenly distributed over the chord than the NACA 230 or symmetrical series airfoils, may be expected to have higher critical Mach numbers for a given lift coefficient because of the absence of local peaks in the pressure distribution.

The maximum lift coefficients of the new airfoils are lower than those obtained in the same Reynolds number range with the NACA 23015 airfoil and slightly lower than those obtained with the NACA 0012 airfoil. Unpublished test results of the NACA 0012 airfoil in the NACA LTT at a Reynolds number of 2.5×10^6 show a maximum lift coefficient of 1.36.

In order to duplicate the low drags obtained in the wind tunnel, the airfoils must be fair and must have the same surface finish in regions of increasing velocity as the wind-tunnel models had. The regions of increasing velocity are shown in the pressure distributions given in the figures. Any surface imperfection, such as specks or waves, that can be felt by hand in the region of increasing velocity is probably large enough to cause transition from laminar to turbulent flow ahead of the position of maximum velocity and thus to cause a rise in drag. A more complete discussion of surface conditions necessary for laminar flow is given in reference 1. The drag that can be expected from the new airfoils when the surface at the nose is very rough is shown in figure 22. This figure contains the results of a test of the NACA 5-H-15 airfoil section with the leading edge of the airfoil covered with a strip of carborundum-covered cellulose "Scotch" tape 2 inches wide that was wrapped around the leading edge. A comparable test of the NACA 23015 airfoil has not been made; a test reported in reference 2 of the NACA 23021 airfoil with the leading edge rough, however, shows this airfoil to be less sensitive to roughness than the low-drag sections presented in the present report. The NACA 23021 airfoil, because of its greater thickness, is probably more sensitive to roughness than the NACA 23015 airfoil.

Another indication of the sensitivity of the low-drag airfoils to roughness is given by the value that the drag on the smooth airfoil reaches just outside the high-lift end of the low-drag range. A sudden rise in drag to large values indicates sudden separation of the flow at the rear of the airfoil. This sudden separation occurs because, at the end of the low-drag range, the boundary layer over the forward portion of the airfoil changes from a thin laminar boundary layer to a relatively thick turbulent boundary layer. With the change to a turbulent boundary layer over the forward portion of the upper surface, the boundary layer at the rear portion cannot overcome the pressure rise occurring on these sections (reference 2).

The figures show that the pitching-moment curves for the low-drag airfoils departed from straight lines in the region at the high-lift end of the low-drag range.

Pitching oscillations with amplitudes of about 2° and a frequency of about 2 cycles per second were observed at the high-lift end of the low-drag range for the NACA 2-H-15, NACA 3-H-13.5, NACA 4-H-12.4, and NACA 6-H-15 airfoil sections, which were tested on the relatively flexible torque rod used in the NACA LTT. No oscillations were observed for the NACA 5-H-15 airfoil under the same test conditions. In addition to the oscillations at the high-lift end of the low-drag range, the NACA 6-H-15 airfoil underwent a sudden and violent oscillation at an angle of attack of -9.3°. The NACA 1-H-15 airfoil section was tested in the NACA LTT on a rigid moment balance that had a stiffness in torsion much greater than the torque arm. No oscillations were noticed during the test of this airfoil. The NACA 23015 airfoil section was tested on the relatively stiff torque arm with which the NACA TDT is fitted. From the character of the lift, drag, and pitching-moment curves obtained for the NACA 23015 airfoil section, no oscillations are to be expected with this airfoil. The oscillations observed for some of the sections are believed to be caused by the rapid change, at the high-lift end of the low-drag range, from the unseparated to the separated type of flow at the tail of the airfoils. The oscillations stopped as soon as the angle of attack was definitely outside the range in which a small change in angle of attack would cause the flow to change from one type to the other. Although oscillations of any type are undesirable, it is believed that the characteristics of the torque arm allowed the airfoils to oscillate for a change in pitching moment which would have been insufficient to cause noticeable oscillations on a stiffer torque arm. The stiffness constant for the torque arm had an average value of 4 foot-pounds per degree deflection.

When airfoils are used as rotor blades, the conditions under which they operate will be different from the test conditions in the wind tunnel. For all conditions of flight, the boundary layers on the blades will be subject to strong centrifugal and aerodynamic pressure gradients and in addition, for conditions of forward flight, the angle of attack, angle of yaw, and velocity will vary rapidly. It is possible that the spanwise pressure gradients may adversely affect the laminar boundary layer and thus the low-drag qualities of the airfoils. The effect of yawed flow may be similar to the effect of the spanwise pressure gradients. The action of the spanwise pressure gradients on the separated region at the rear of the airfoils, which is present when the drags of the airfoils are high, is likely to be beneficial. The forces acting along the span of the blades will tend to make the separated flow run out along the blade span, and the Coriolis forces will tend to sweep the separated flow off the trailing edge. The rapidly changing angle of attack in forward flight may not provide sufficient time for the boundary layers to build up to the steady values associated with the section characteristics obtained from the wind-tunnel tests. In forward flight, the effect of the rapid changes in velocity over the sections of the blades may be similar to the effect of the rapidly changing angles of attack.

It is recommended that a rotor using low-drag sections be built and tested full scale. Such a test would serve to indicate whether the sum of all possible differences between the wind-tunnel test conditions and the rotor conditions would be sufficient to affect noticeably the rotor characteristics. Tests of rotors that have different sections would also serve to indicate the extent to which section characteristics affect rotor characteristics.

CONCLUDING REMARKS

New airfoil sections that have small or zero pitching-moment coefficients and high lift-drag ratios have been developed and tested. With sections having pitching-moment coefficients close to zero, maximum section lift-drag ratios that were almost twice as great as those which have been attained on sections of the NACA 230-series airfoils were attained in the Reynolds number range from 1.7×10^6 to 3.2×10^6. The new airfoil sections, because of their small pitching moments and low profile-drag coefficients at moderate lift coefficients, may be suitable for use on the rotor blades of rotating-wing aircraft. It is desirable, however, that some of these sections be tested on a full-scale rotor to observe their characteristics in actual rotor use and to determine whether certain undesirable characteristics, such as sensitivity to surface roughness and change in pitching moment, which were noticed in the tunnel, have a serious effect when the sections are applied to rotor blades.

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REFERENCES

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2. Jacobs, Eastman N., Abbott, Ira H., and Davidson, Milton: Investigation of Extreme Leading-Edge Roughness on Thick Low-Drag Airfoils to Indicate Those Critical to Separation. NACA C. B., June 1942.

TABLE I

AIRFOIL-SECTION ORDINATES

[Stations and ordinates in percent of airfoil chord]

NACA 1-H-15			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
-0.087	1.448	-0.077	-0.042
.5	2.232	.5	-.655
.75	2.488	.75	-.739
1.25	2.931	1.25	-.887
2.5	3.813	2.5	-1.121
5.0	5.177	5.0	-1.304
7.5	6.305	7.5	-1.367
10	7.276	10	-1.400
15	8.916	15	-1.437
20	10.267	20	-1.453
25	11.363	25	-1.458
30	12.217	30	-1.483
35	12.831	35	-1.517
40	13.166	40	-1.565
45	13.243	45	-1.620
50	13.017	50	-1.679
55	12.428	55	-1.721
60	11.459	60	-1.754
65	10.073	65	-1.766
70	8.272	70	-1.761
75	6.151	75	-1.717
80	3.987	80	-1.614
85	2.031	85	-1.460
90	.538	90	-1.200
95	-.261	95	.797
100	0	100	0

NACA 2-H-15			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
-0.087	1.448	-0.077	-0.042
.5	2.232	.5	-.655
.75	2.488	.75	-.739
1.25	2.931	1.25	-.887
2.5	3.813	2.5	-1.121
5.0	5.177	5.0	-1.304
7.5	6.305	7.5	-1.367
10	7.276	10	-1.400
15	8.916	15	-1.437
20	10.267	20	-1.453
25	11.363	25	-1.458
30	12.217	30	-1.483
35	12.831	35	-1.517
40	13.166	40	-1.565
45	13.243	45	-1.620
50	13.017	50	-1.679
55	12.428	55	-1.721
60	11.459	60	-1.754
65	10.073	65	-1.766
70	8.340	70	-1.660
75	6.420	75	-1.470
80	4.650	80	-1.160
85	3.280	85	-.710
90	2.370	90	-.090
95	1.870	95	.730
100	1.750	100	1.750

TABLE I

AIRFOIL-SECTION ORDINATES - Continued

NACA 3-H-13.5			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
-0.079	1.316	-0.070	-0.038
.454	2.029	.454	-.595
.682	2.262	.682	-.672
1.136	2.665	1.136	-.806
2.273	3.466	2.273	-1.019
4.546	4.706	4.546	-1.185
6.818	5.732	6.818	-1.243
9.091	6.615	9.091	-1.273
13.636	8.105	13.636	-1.306
18.182	9.334	18.182	-1.321
22.727	10.330	22.727	-1.325
27.273	11.106	27.273	-1.348
31.818	11.664	31.818	-1.379
36.364	11.969	36.364	-1.423
40.909	12.039	40.909	-1.473
45.454	11.834	45.454	-1.526
50.000	11.298	50.000	-1.565
54.546	10.417	54.546	-1.595
59.091	9.157	59.091	-1.605
63.636	7.727	63.636	-1.601
68.182	6.309	68.182	-1.561
72.727	4.955	72.727	-1.467
77.273	3.782	77.273	-1.264
81.818	2.873	81.818	-.991
86.364	2.282	86.364	-.564
90.909	1.873	90.909	0
95.454	1.655	95.454	.718
100.000	1.591	100.000	1.591

NACA 4-H-12.4			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
-0.072	1.207	-0.064	-0.035
.417	1.860	.417	-.546
.625	2.073	.625	-.616
1.042	2.442	1.042	-.739
2.083	3.178	2.083	-.934
4.167	4.314	4.167	-1.087
6.250	5.254	6.250	-1.139
8.333	6.063	8.333	-1.167
12.500	7.430	12.500	-1.198
16.667	8.556	16.667	-1.211
20.833	9.469	20.833	-1.215
25.000	10.181	25.000	-1.236
29.167	10.692	29.167	-1.264
33.333	10.972	33.333	-1.304
37.500	11.036	37.500	-1.350
41.667	10.848	41.667	-1.399
45.833	10.357	45.833	-1.434
50.000	9.549	50.000	-1.417
54.167	8.394	54.167	-1.472
58.333	7.150	58.333	-1.468
62.500	5.933	62.500	-1.450
66.667	4.800	66.667	-1.433
70.833	3.750	70.833	-1.392
75.000	2.808	75.000	-1.333
79.167	1.983	79.167	-1.233
83.333	1.300	83.333	-1.083
87.500	.733	87.500	-.900
91.667	.325	91.667	-.658
95.833	.083	95.833	-.358
100.000	0	100.000	0

TABLE I

AIRFOIL-SECTION ORDINATES - Continued

NACA 5-H-15			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.192	1.225	.808	-.881
.409	1.501	1.091	-1.015
.861	1.973	1.639	-1.229
2.040	2.899	2.960	-1.599
4.476	4.294	5.524	-2.080
6.953	5.390	8.047	-2.422
9.454	6.311	10.546	-2.685
14.492	7.774	15.508	-3.090
19.565	8.904	20.435	-3.394
24.663	9.734	25.337	-3.626
29.782	10.331	30.218	-3.819
34.922	10.709	35.078	-3.993
40.090	10.841	39.910	-4.123
45.291	10.708	44.709	-4.250
50.635	10.171	49.365	-4.351
55.759	9.275	54.241	-4.459
60.772	8.193	59.228	-4.547
65.703	6.955	64.297	-4.541
70.575	5.658	69.425	-4.426
75.400	4.356	74.600	-4.166
80.157	3.098	79.843	-3.666
84.996	2.003	85.004	-2.793
89.968	1.037	90.032	-1.693
94.983	.372	95.017	-.656
100.000	0	100.000	0
L. E. radius: 1.42			

NACA 6-H-15			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.097	1.252	.903	-.788
.302	1.552	1.198	-.896
.736	2.068	1.764	-1.064
1.889	3.090	3.111	-1.334
4.300	4.647	5.700	-1.659
6.768	5.878	8.232	-1.872
9.267	6.919	10.733	-2.023
14.317	8.575	15.683	-2.251
19.414	9.855	20.586	-2.417
24.546	10.796	25.454	-2.550
29.706	11.468	30.294	-2.676
34.895	11.883	35.105	-2.817
40.121	12.017	39.879	-2.947
45.392	11.834	44.608	-3.116
50.855	11.168	49.145	-3.310
56.020	10.084	53.980	-3.582
61.035	8.794	58.965	-3.872
65.943	7.343	64.057	-4.085
70.772	5.848	69.228	-4.184
75.538	4.374	74.462	-4.118
80.211	2.996	79.789	-3.762
84.994	1.865	85.006	-2.931
89.957	.980	90.043	-1.798
94.977	.322	95.023	-.706
100.000	0	100.000	0
L. E. radius: 1.42			

TABLE I

AIRFOIL-SECTION ORDINATES - Concluded

NACA 23015			
Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	-----	0	0
1.25	3.34	1.25	-1.54
2.5	4.44	2.5	-2.25
5.0	5.89	5.0	-3.04
7.5	6.90	7.5	-3.61
10	7.64	10	-4.09
15	8.52	15	-4.84
20	8.92	20	-5.41
25	9.08	25	-5.78
30	9.05	30	-5.96
40	8.59	40	-5.92
50	7.74	50	-5.50
60	6.61	60	-4.81
70	5.25	70	-3.91
80	3.73	80	-2.83
90	2.04	90	-1.59
95	1.12	95	-.90
100	(.16)	100	(-.16)
100	-----	100	0
L. E. radius: 2.48. Slope of radius through end of chord: 0.305			

TABLE II

AIRFOIL SECTION CHARACTERISTICS

Airfoil	$(c_l/c_d)_{max}$	Reynolds number, R	$c_{m_{a.c.}}$	Low-drag range	$(t/c)_{max}$	t/c at x/c=0.25	$c_{l_{max}}$	Reynolds number, R	Critical Mach number	c_l	Chord (in.)	Aerodynamic center (percent c ahead of c/4)
NACA 1-H-15	216	2.60×10^6	-0.052	0.55 to 1.05	0.1486	0.1282	1.29	2.60×10^6	0.58	0.53	24	0
NACA 2-H-15	168	2.67	-0.029	0.51 to 0.87	.1486	.1282	1.29	2.39	.56	.70	24	0
NACA 3-H-13.5	163	2.60	0.003	0.38 to 0.88	.1352	.1208	1.20	2.94	.56	.60	26.6	0
NACA 4-H-12.4	184	2.60	-0.010	0.47 to 1.00	.1239	.1142	1.30	2.60	.55	.65	28.8	-1.70
NACA 5-H-15	131	2.67	0.002	0.16 to 0.77	.1500	.1339	1.14	2.67	.60	.42	24	0
NACA 6-H-15	143	2.58	0	0.30 to 0.94	.1500	.1339	1.17	2.42	.57	.59	24	0
NACA 23015	101	2.60	-0.005	----	.1500	.1486	1.52	2.60	.54	.50	24	1.25

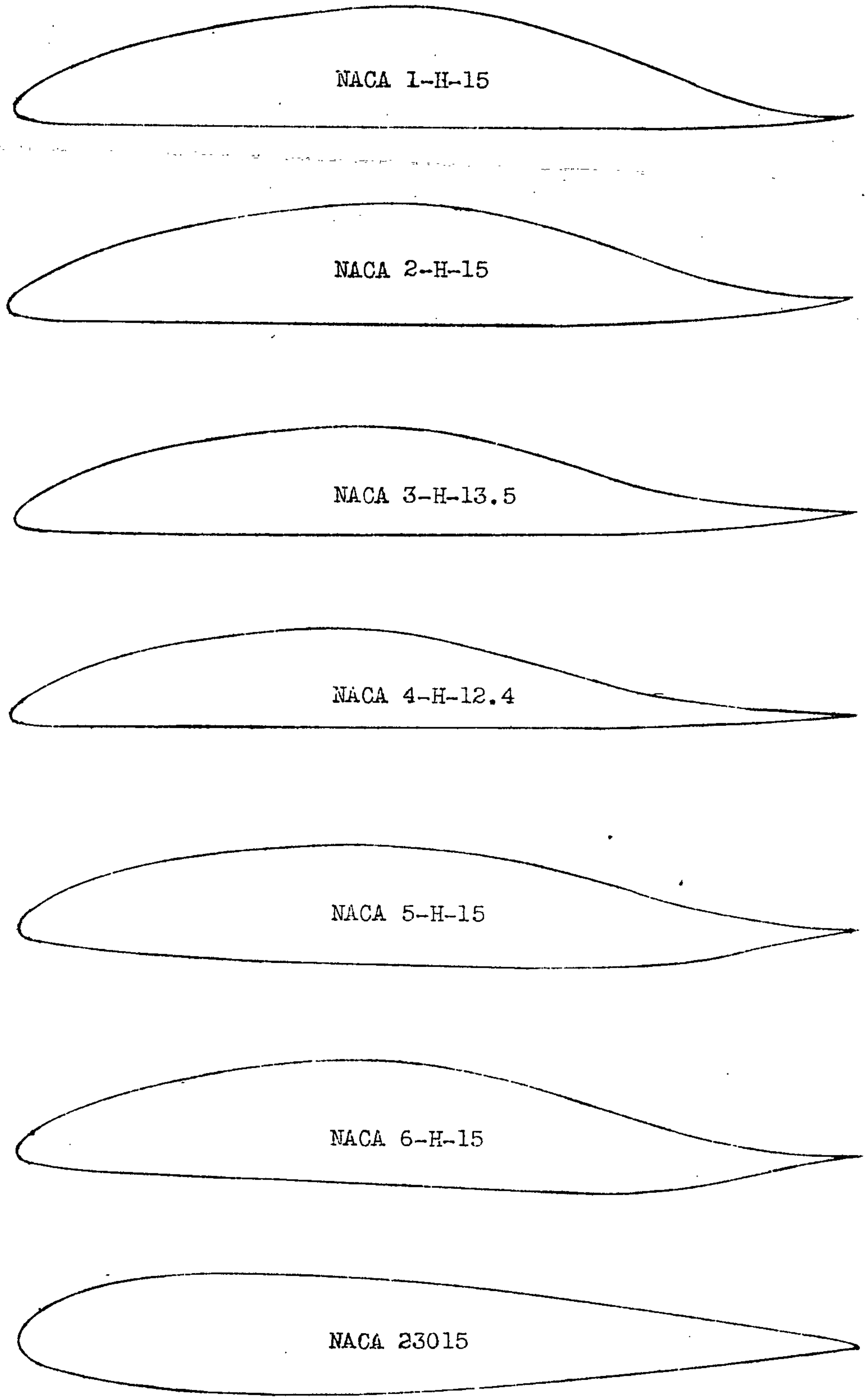

Figure 1.- Airfoil sections

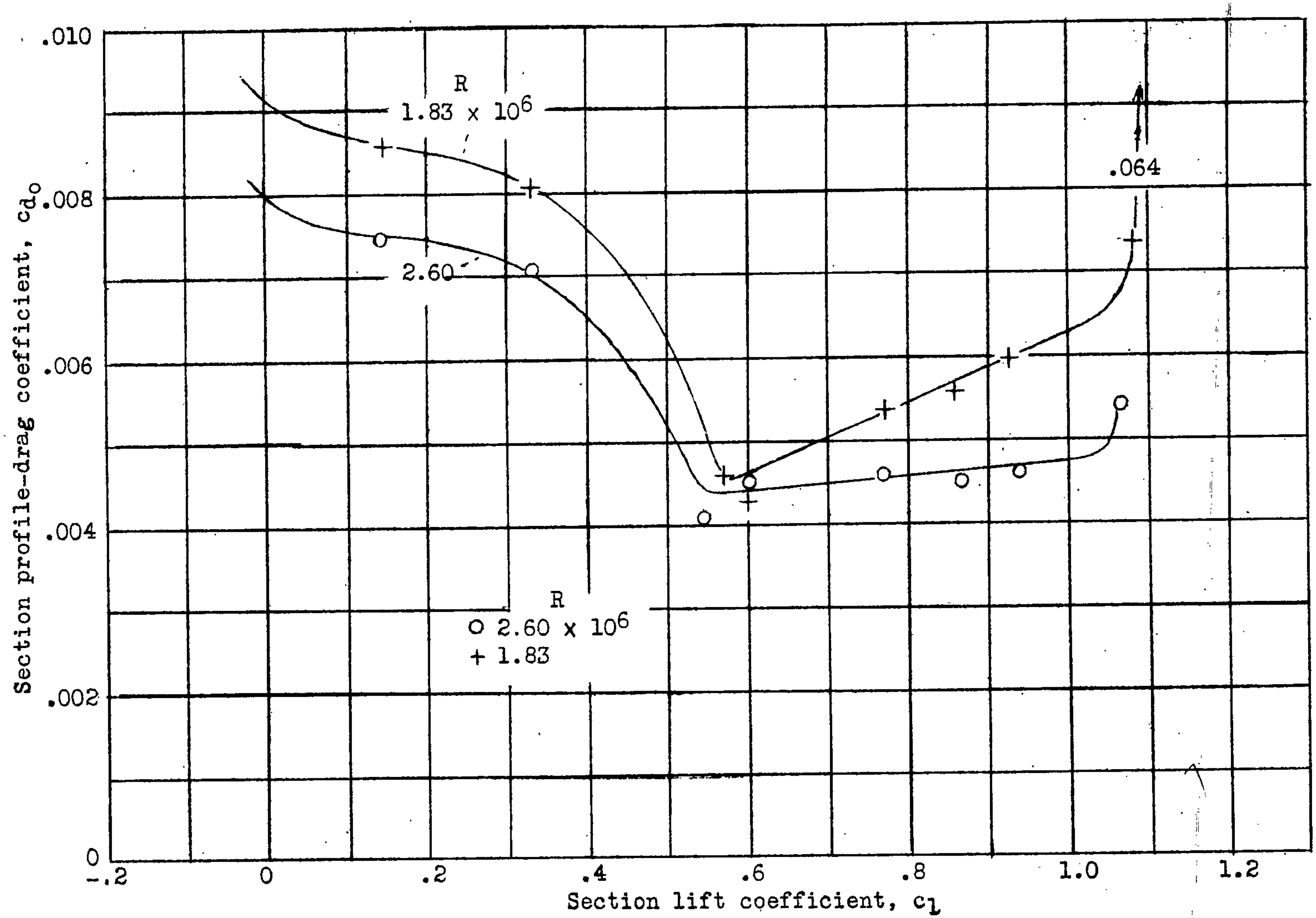

Figure 2.- Lift-drag polar for NACA 1-H-15 airfoil section.

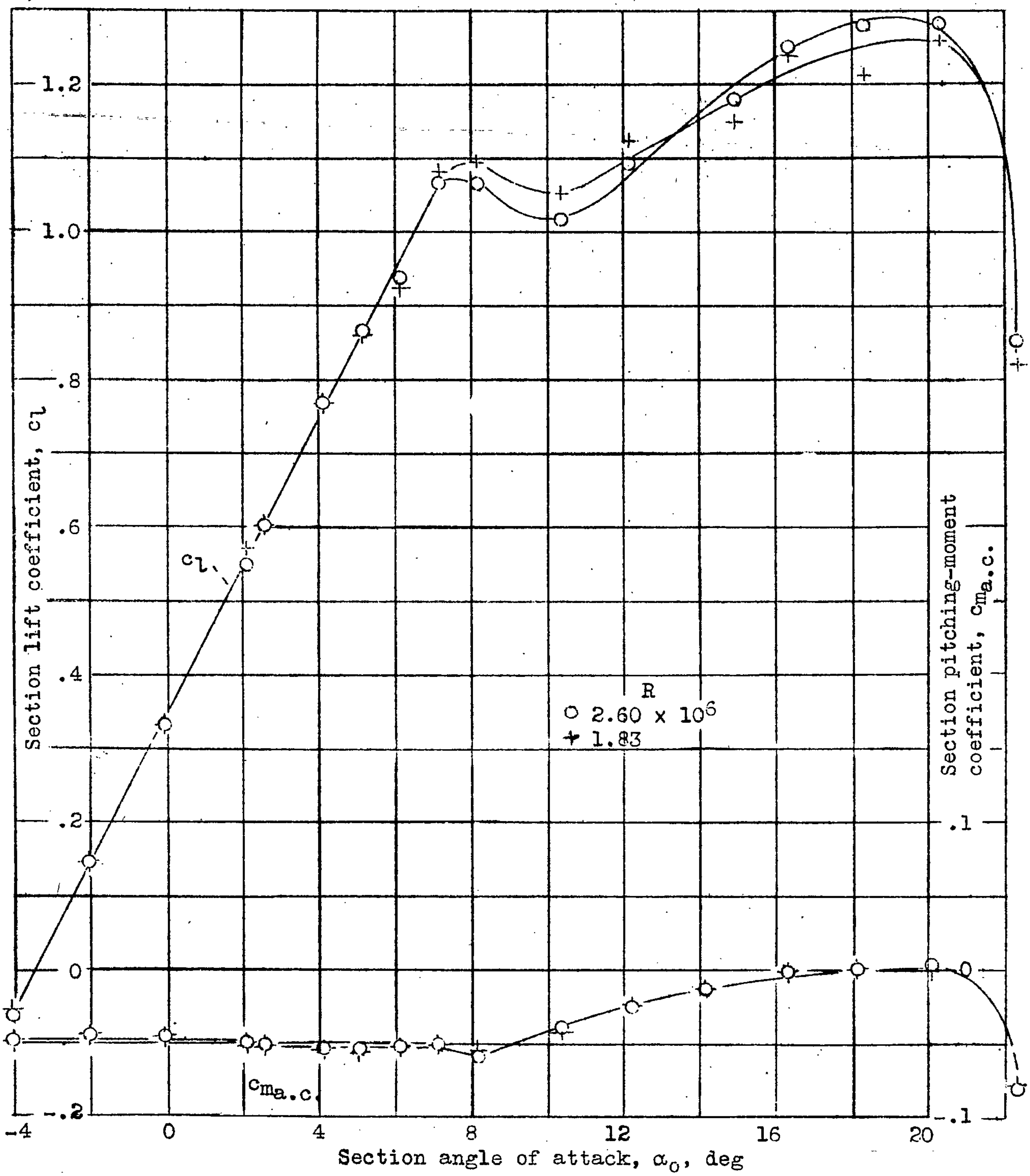

Figure 3.- Variation of c_l and $c_{m_{a.c.}}$ with α_o for NACA 1-H-15 airfoil section.

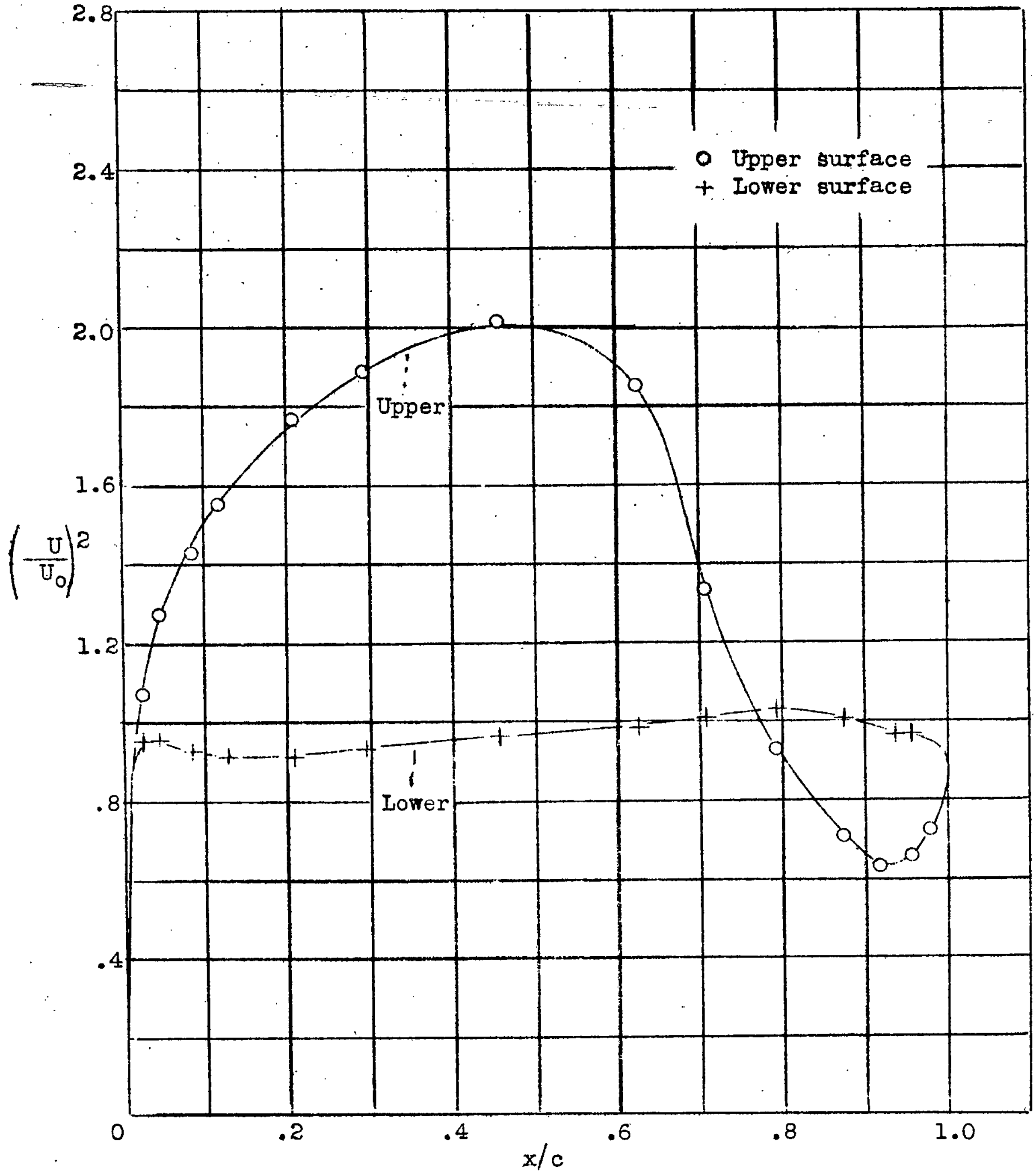

Figure 4.- Pressure distribution on NACA 1-H-15 airfoil section at $c_l = 0.53$. $R = 2.60 \times 10^6$.

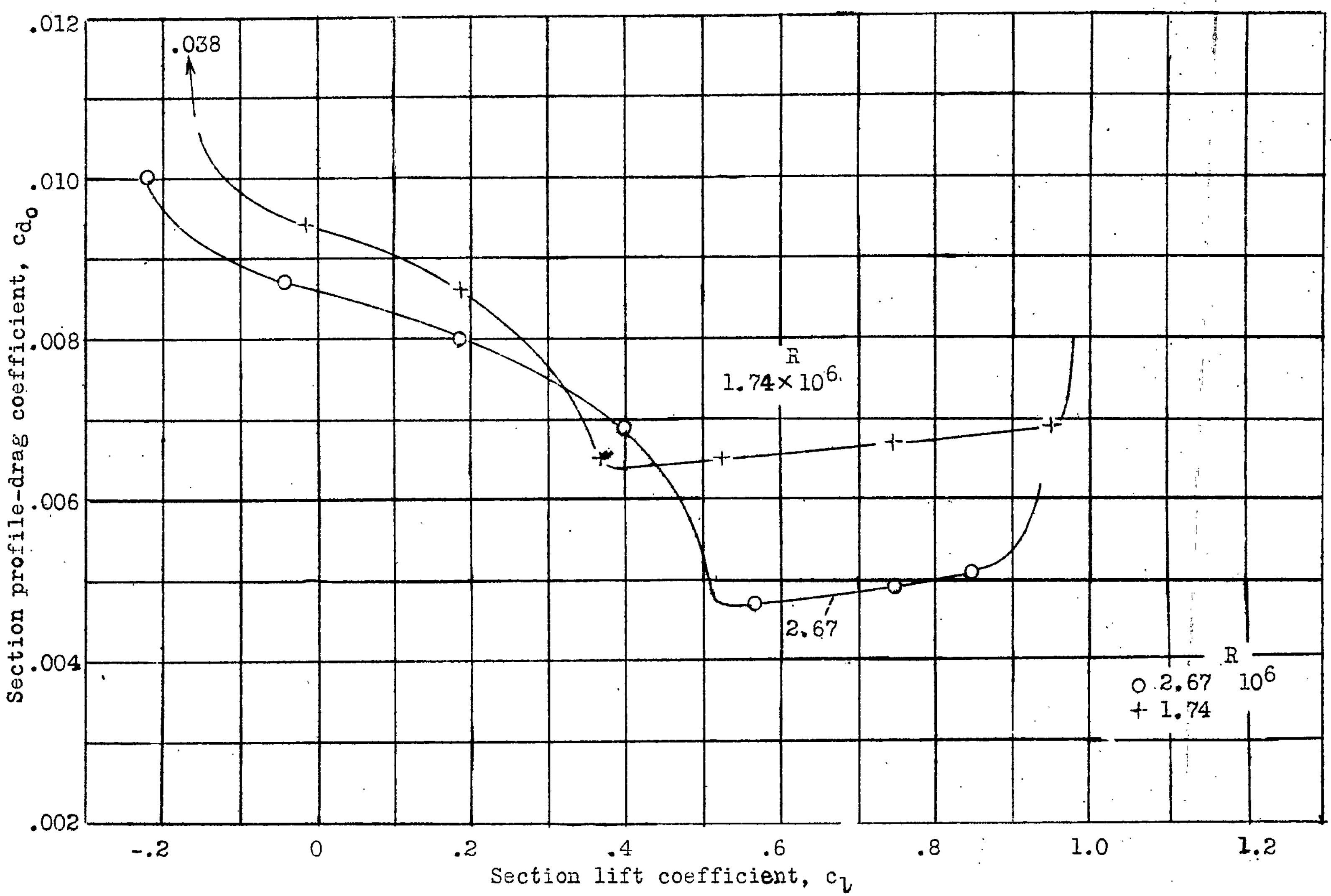

Figure 5.- Lift-drag polar for NACA 2-H-15 airfoil section.

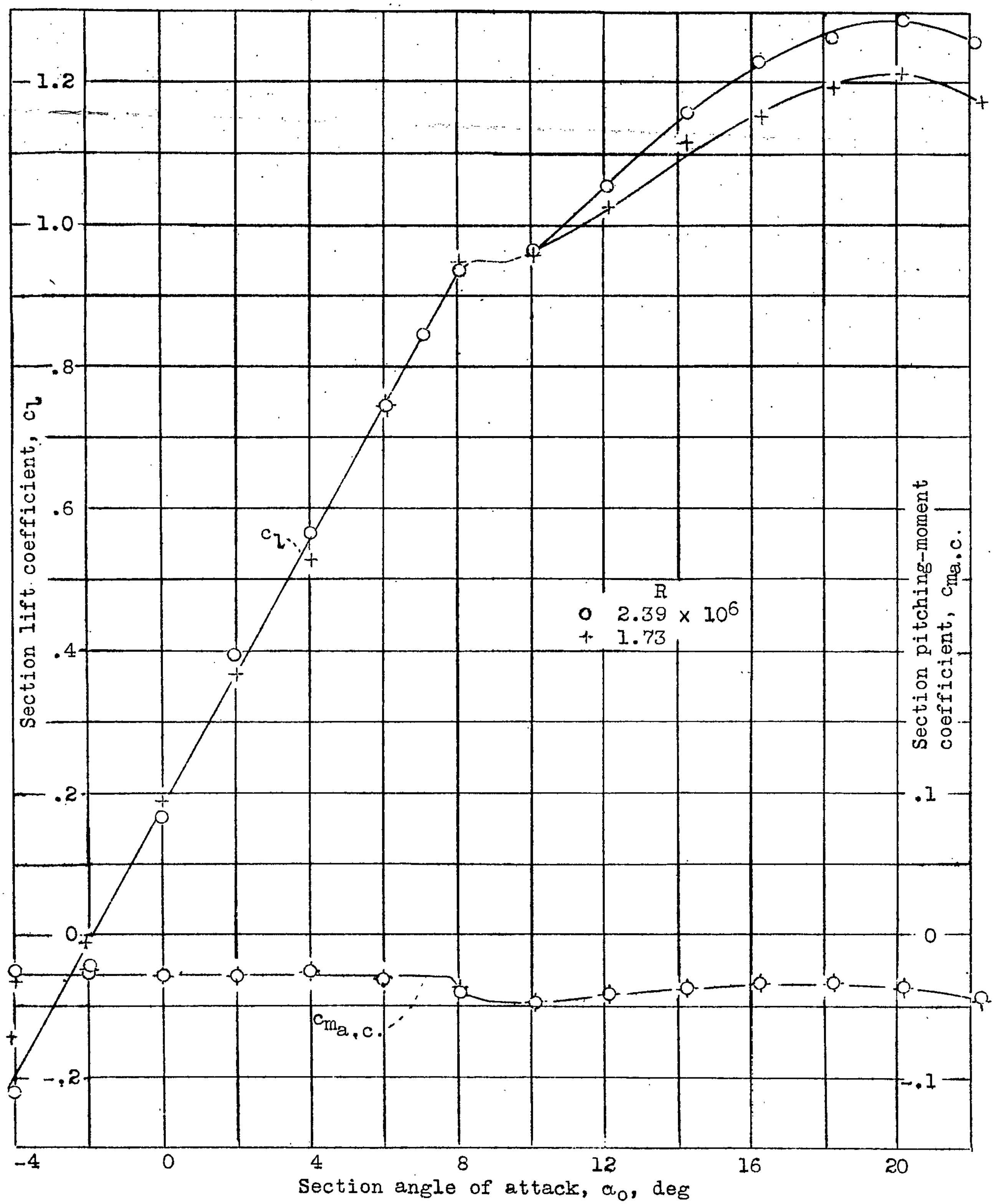

Figure 6.- Variation of c_l and $c_{m_{a.c.}}$ with α_o for NACA 2-H-15 airfoil section.

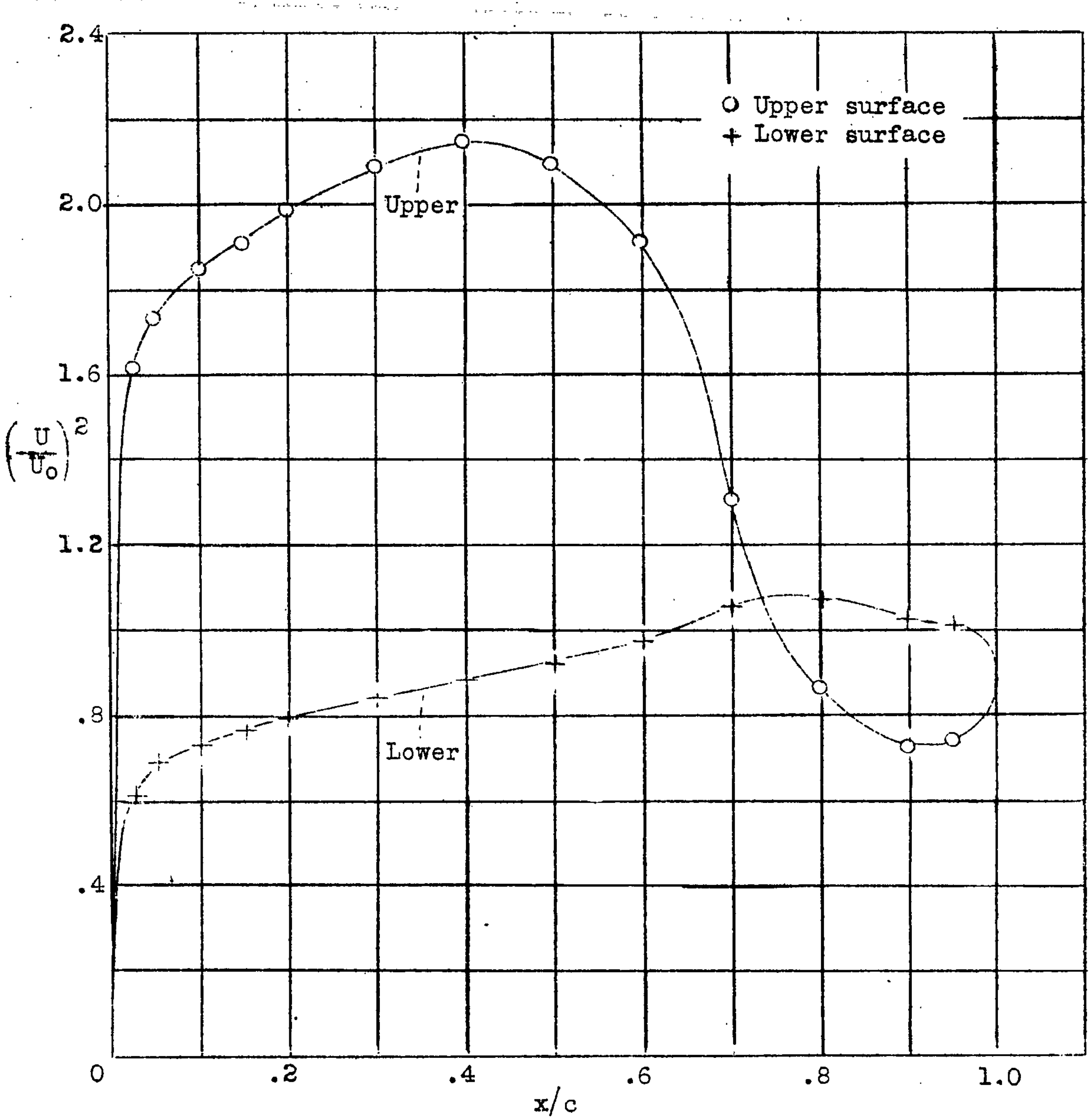

Figure 7.- Pressure distribution on NACA 2-H-15 airfoil section at $c_l = 0.70$. $R = 2.67 \times 10^6$.

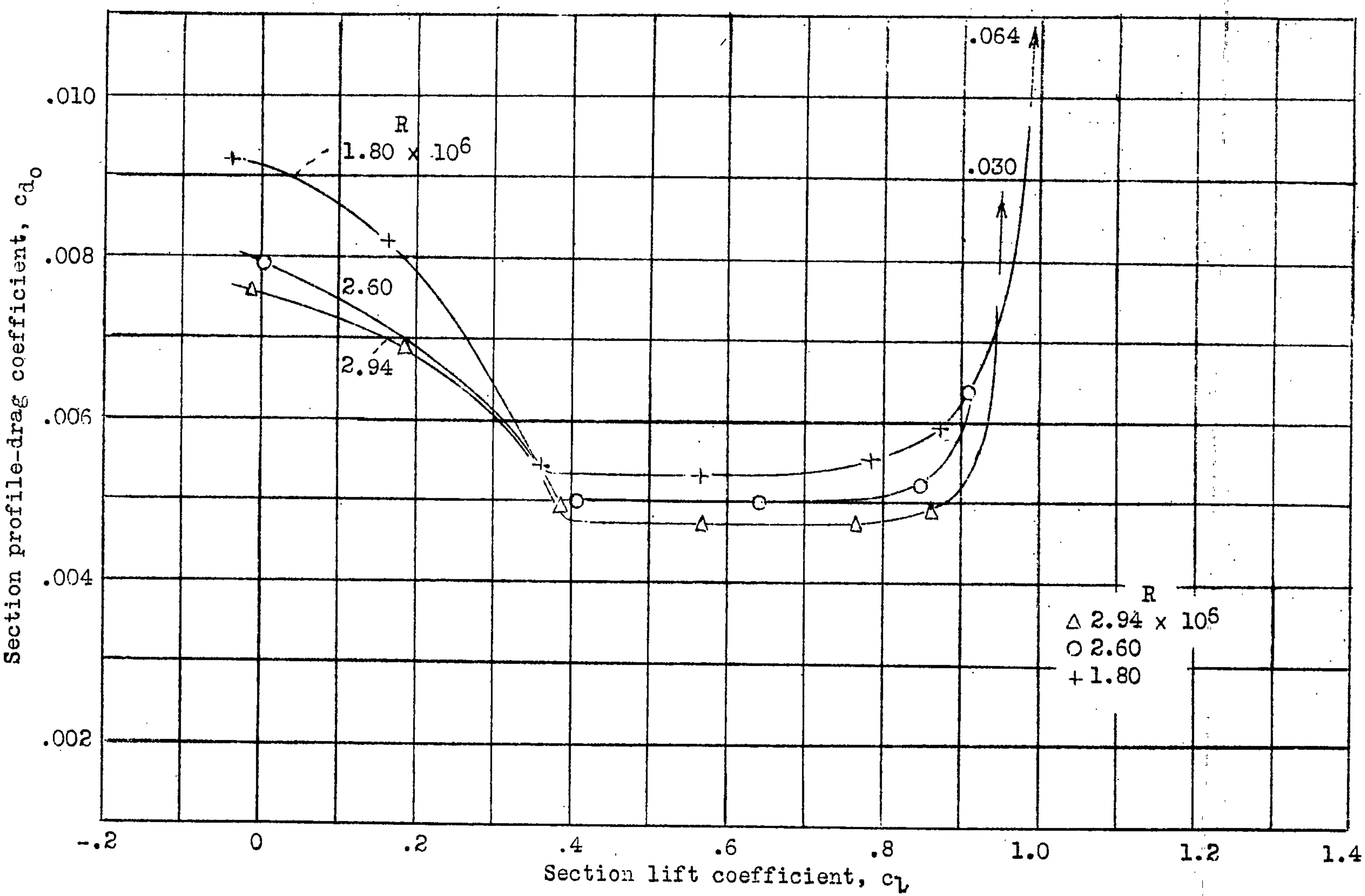

Figure 8.- Lift-drag polar for NACA 3-H-13.5 airfoil section.

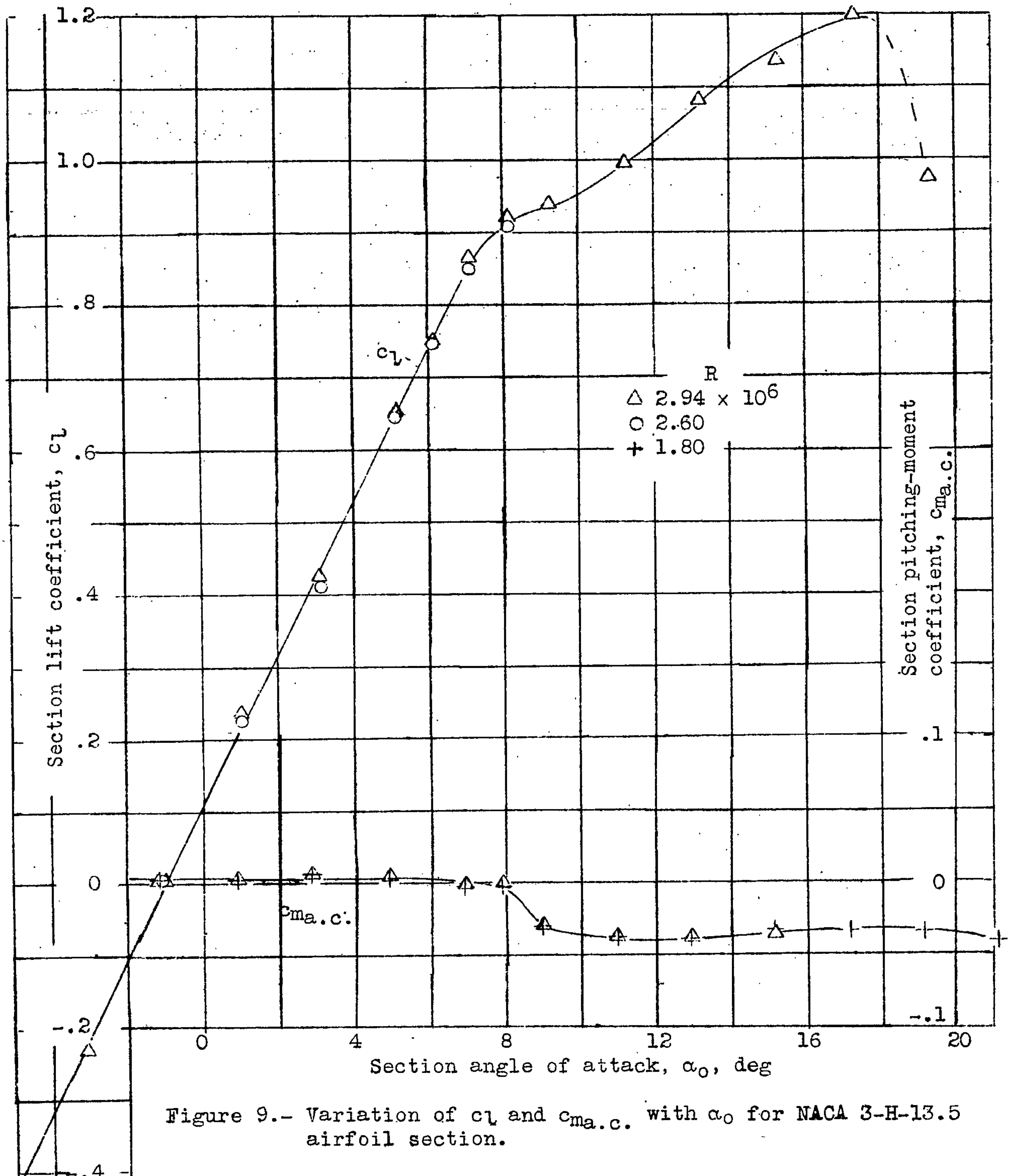

Figure 9.- Variation of c_l and $c_{m_{a.c.}}$ with α_0 for NACA 3-H-13.5 airfoil section.

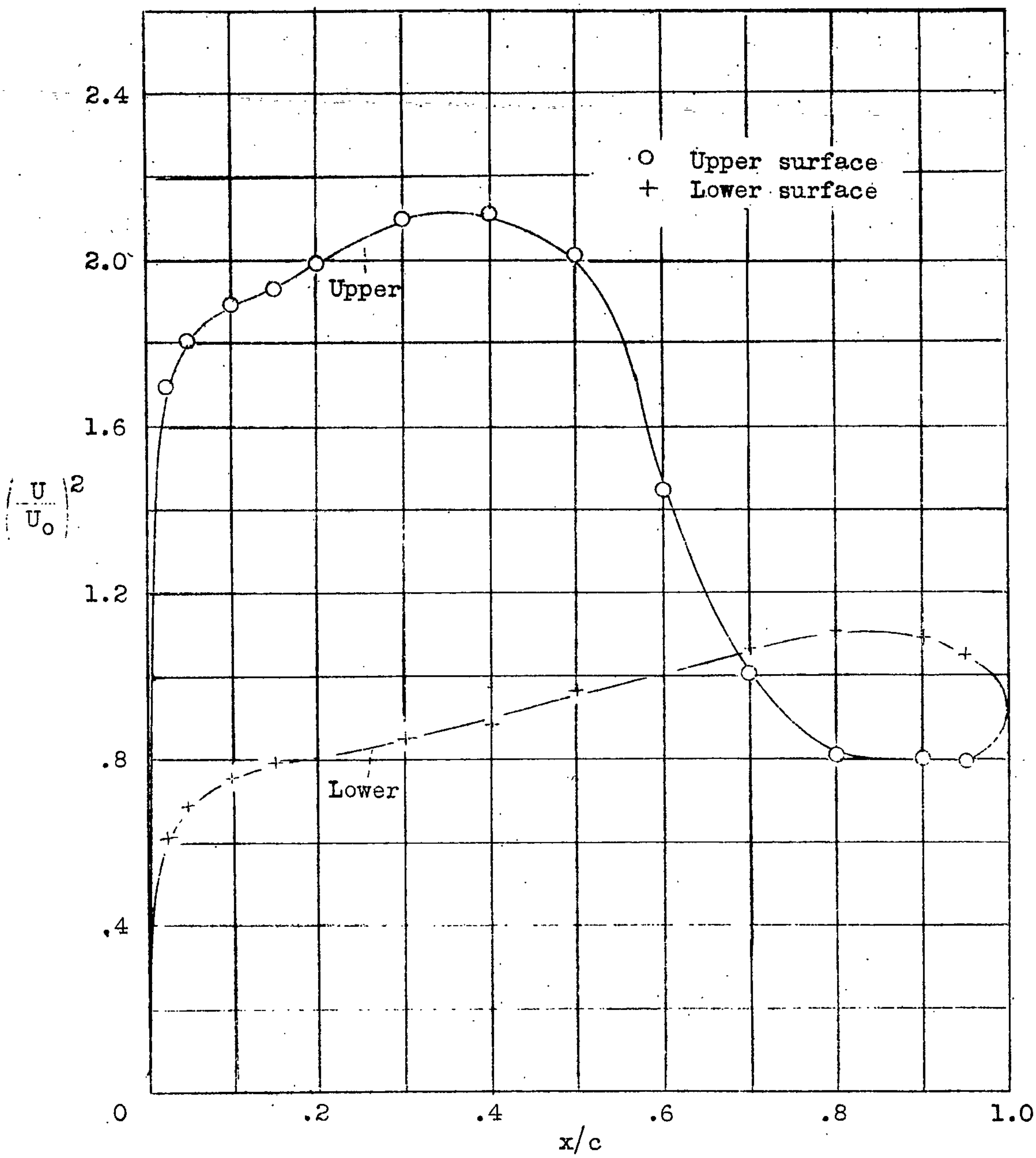

Figure 10.- Pressure distribution on NACA 3-H-13.5 airfoil section at c_l = 0.60. R = 2.94 x 10^6.

NACA

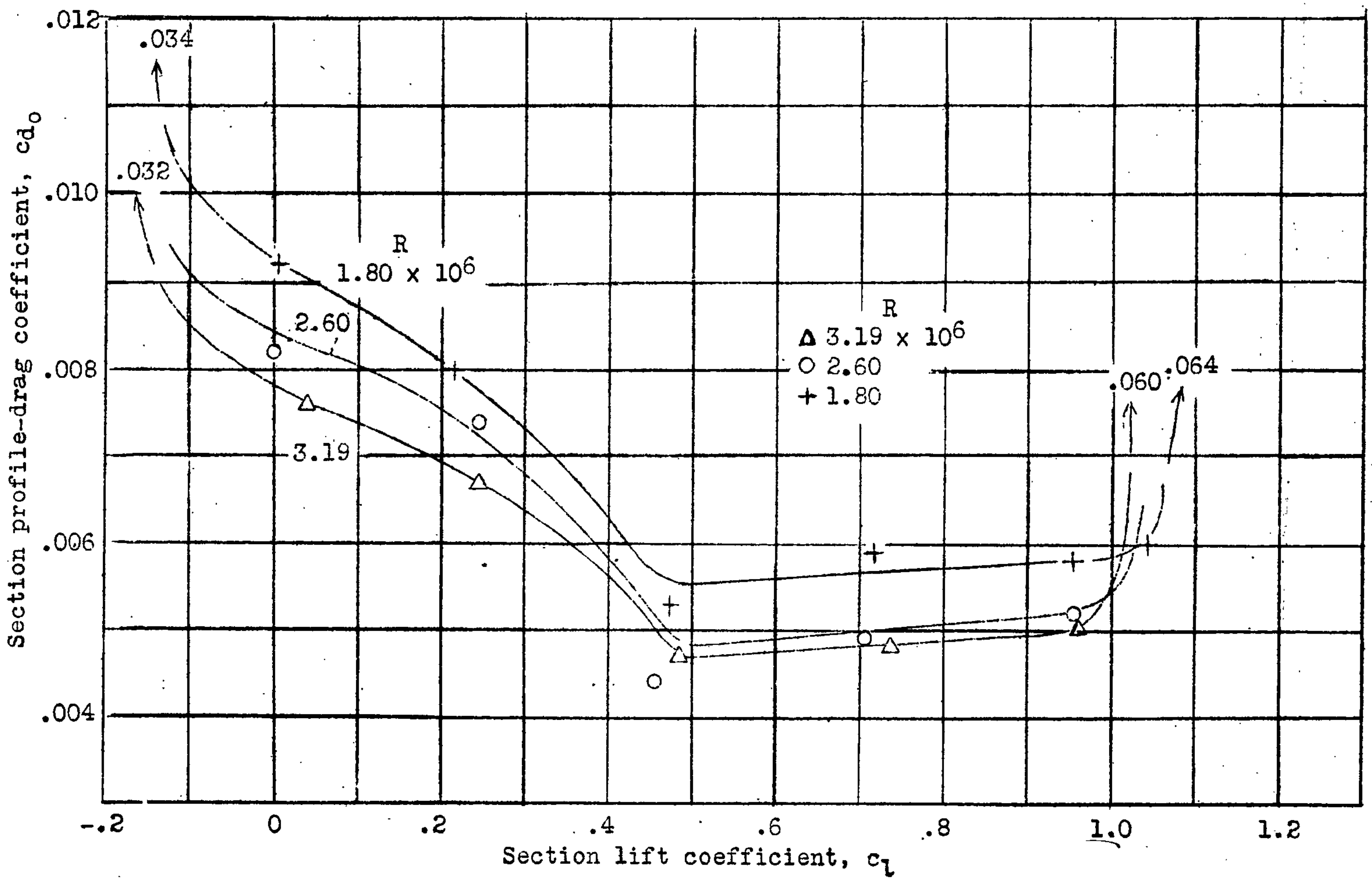

Figure 11.- Lift-drag polar for NACA 4-H-12.4 airfoil section.

Fig. 11

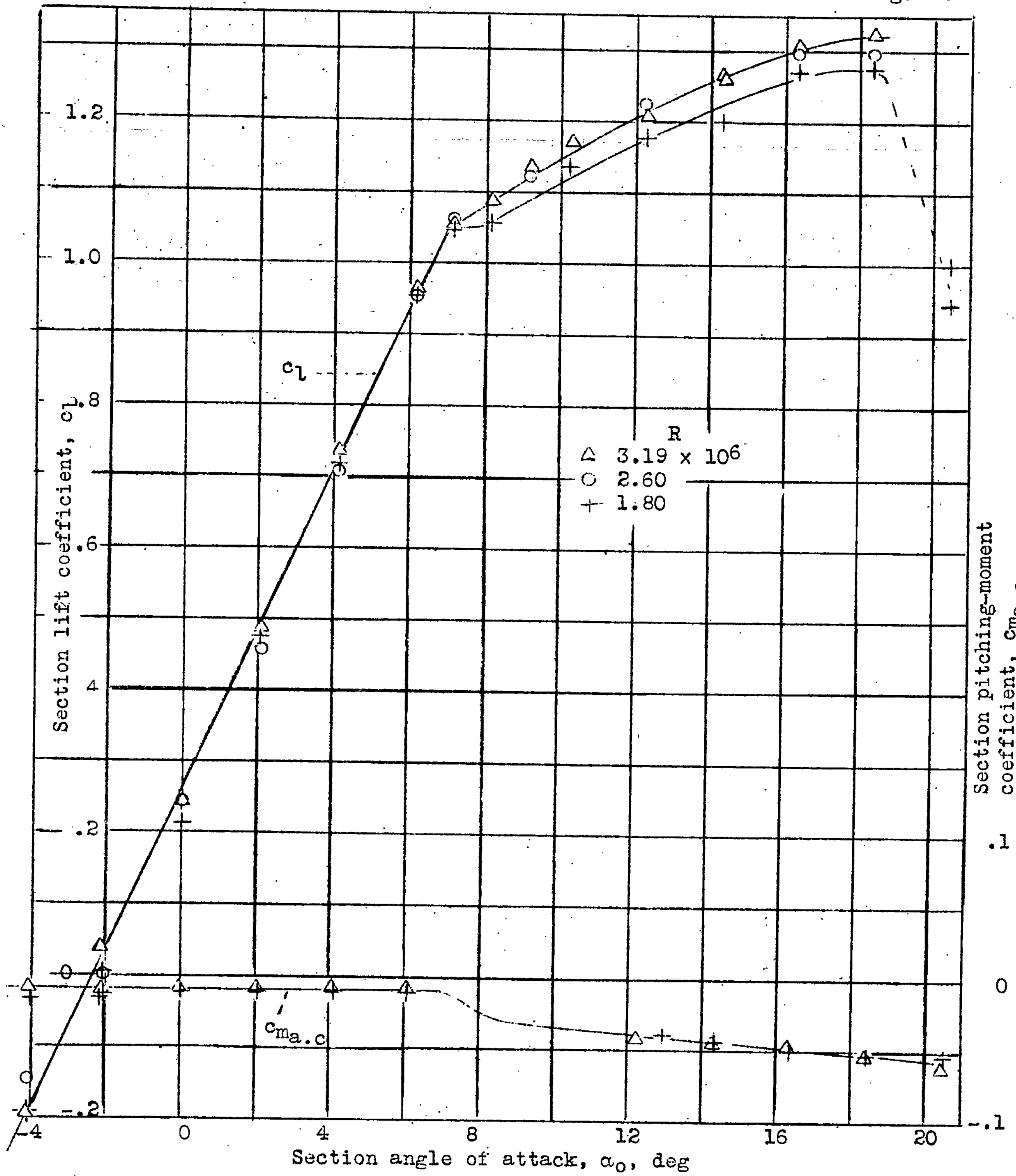

Figure 12.- Variation of c_l and $c_{m_{a.c.}}$ with α_o for NACA 4-H-12.4 airfoil section.

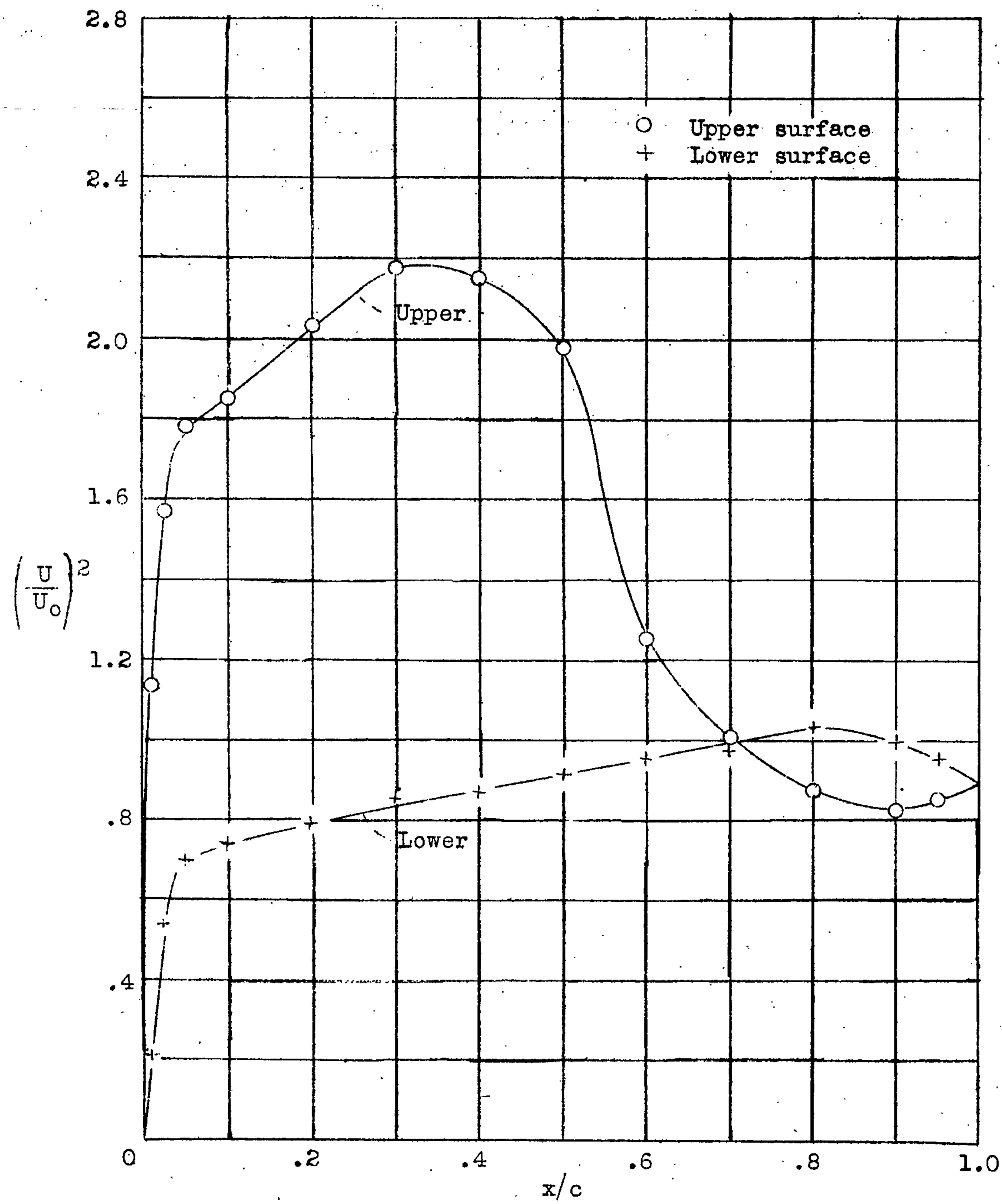

Figure 13.- Pressure distribution on NACA 4-H-12.4 airfoil section at c_l = 0.65. R = 2.60 x 10^6.

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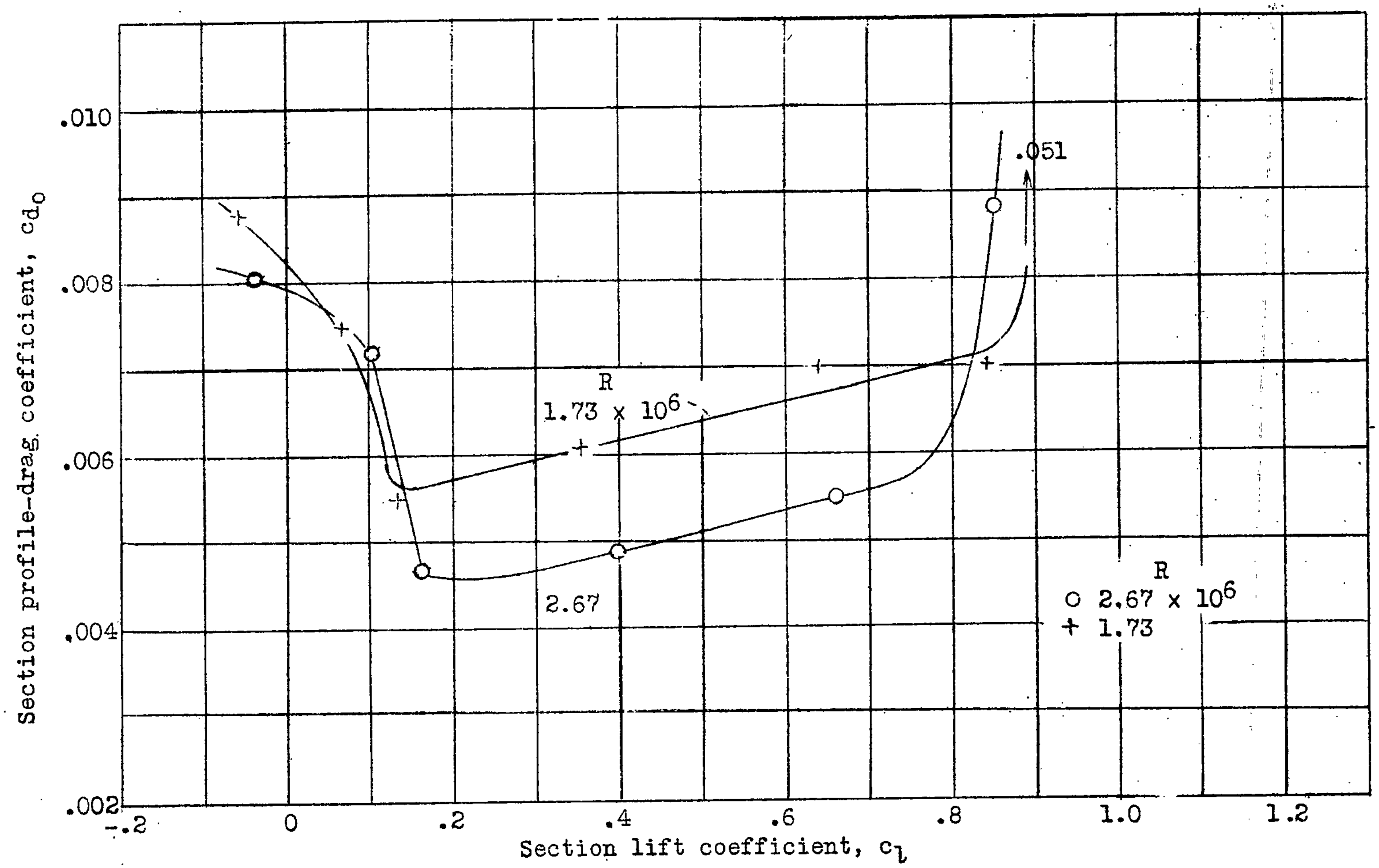

Figure 14.- Lift-drag polar for NACA 5-H-15 airfoil section.

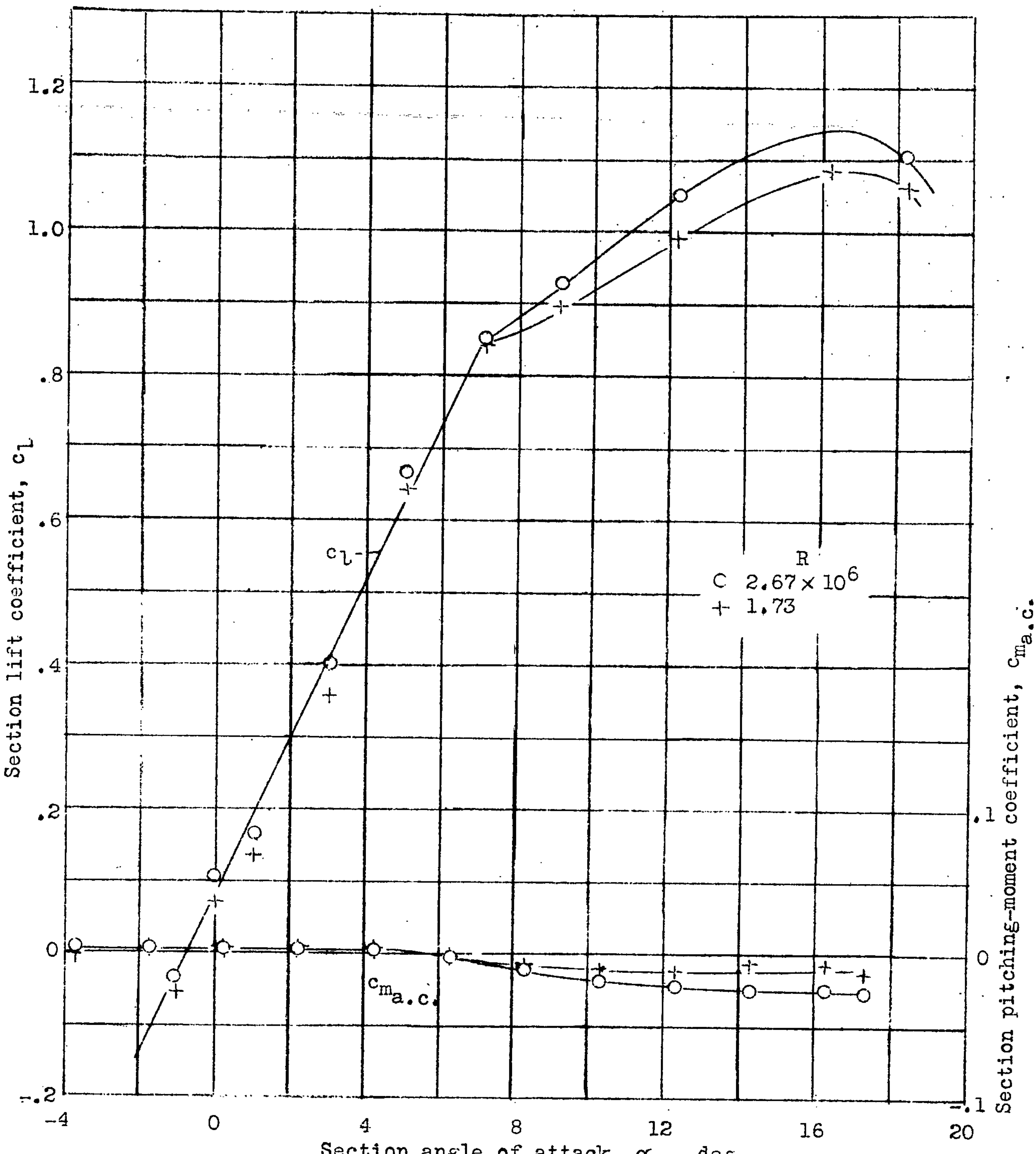

Figure 15.- Variation of c_l and $c_{m_{a.c.}}$ with α_0 for NACA 5-H-15 airfoil section.

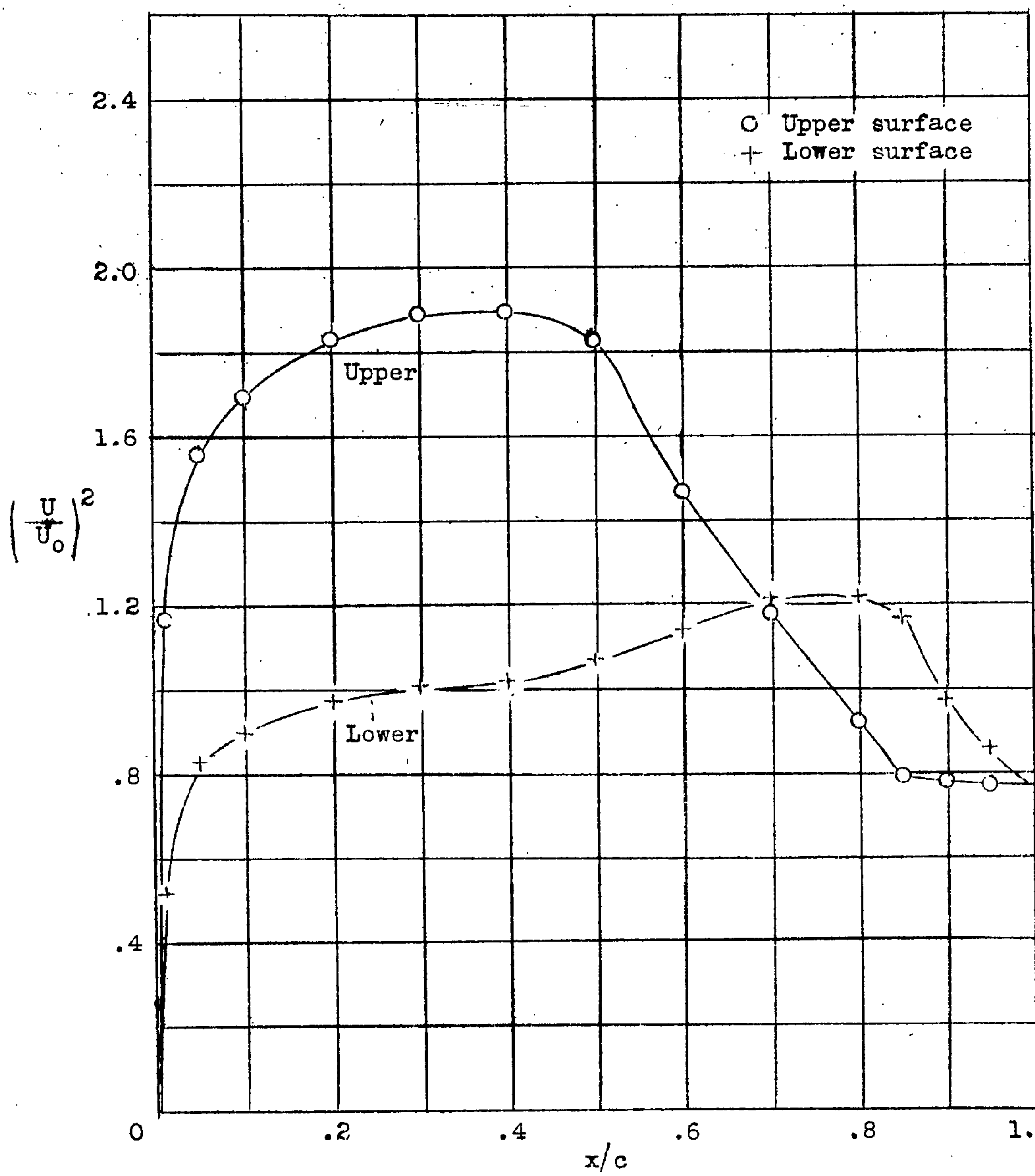

Figure 16.- Pressure distribution on NACA 5-H-15 airfoil section at c_l = 0.42. R = 2.67 x 10^6.

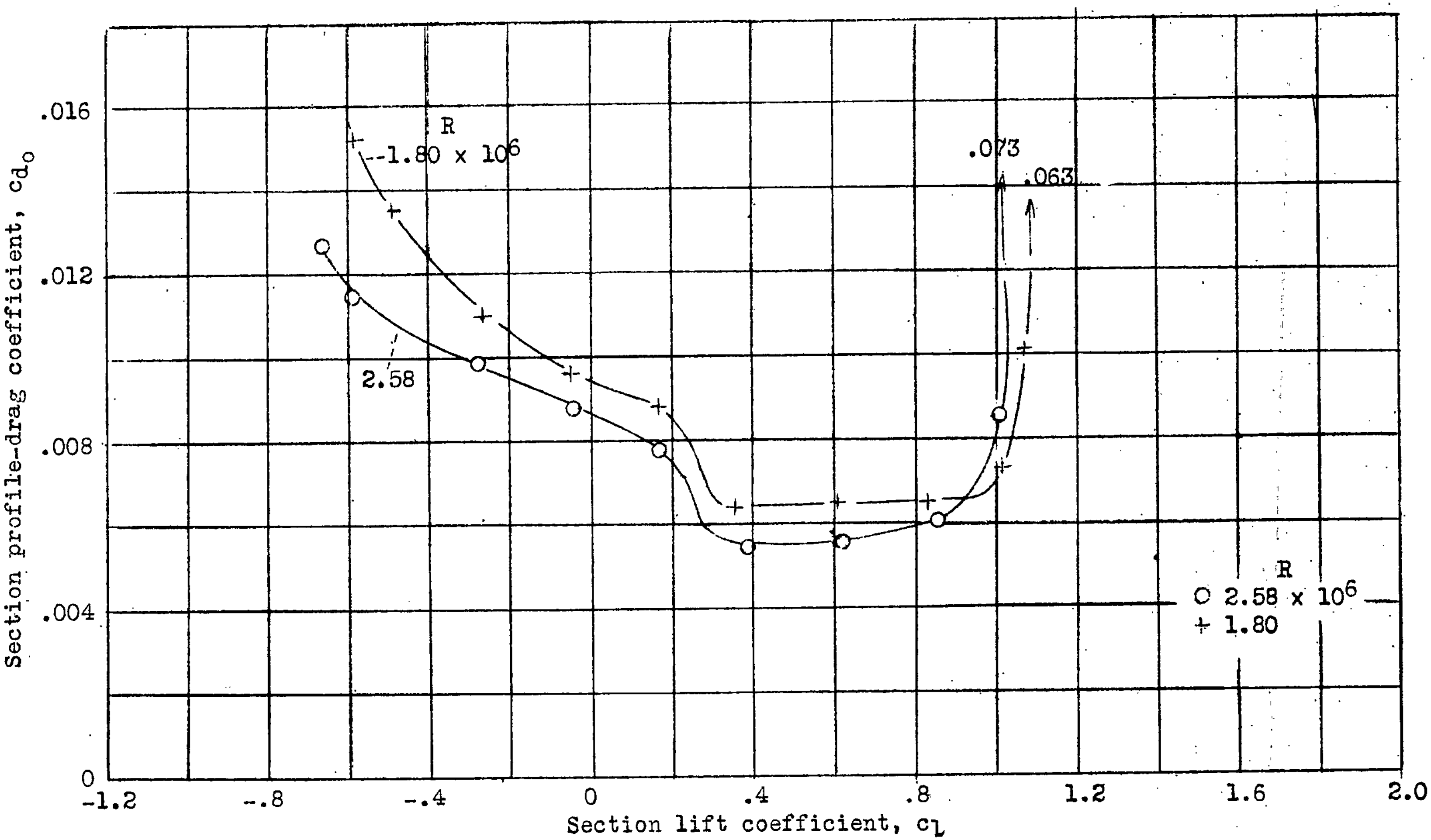

Figure 17.- Lift-drag polar for NACA 6-H-15 airfoil section.

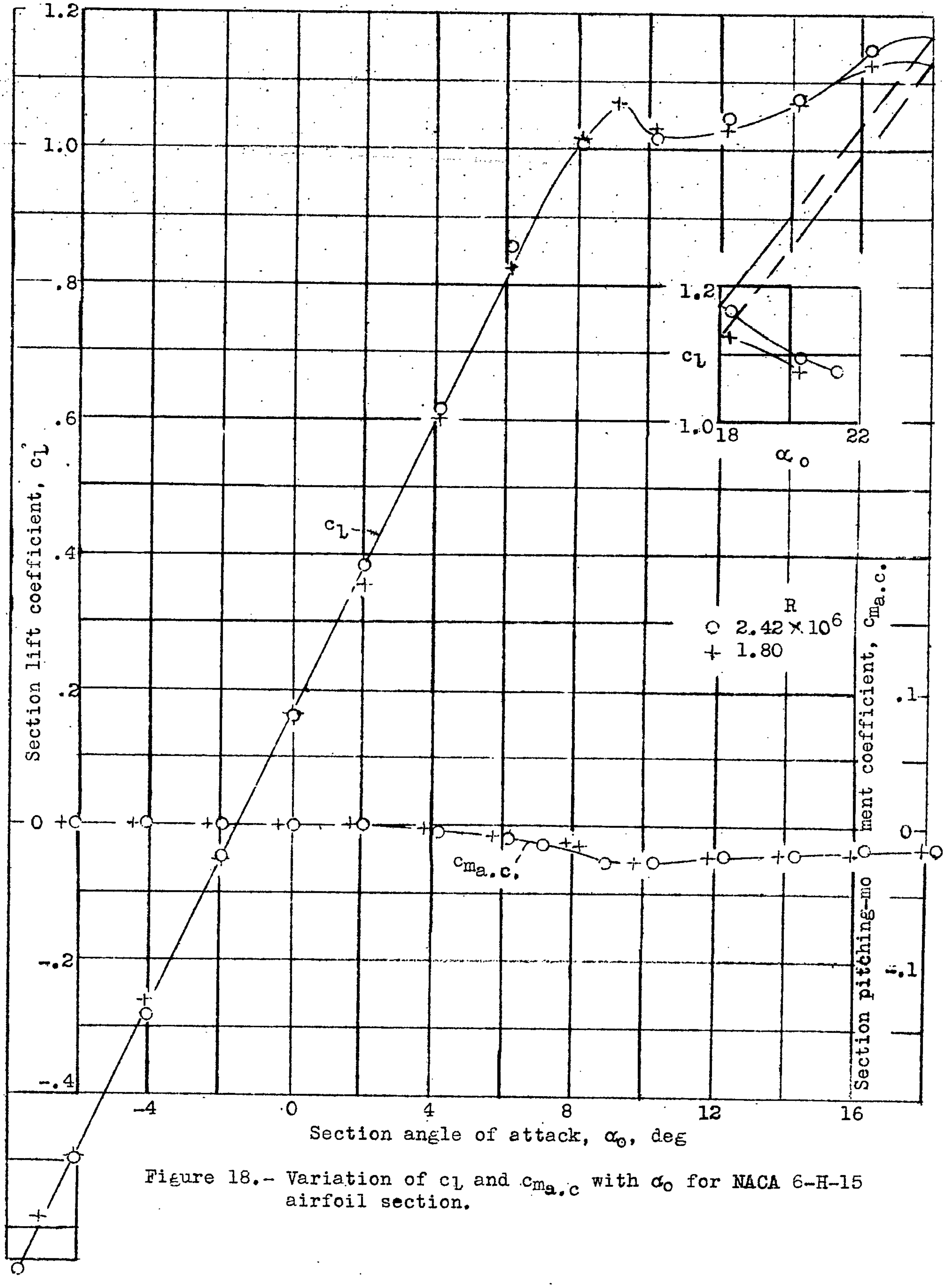

Figure 18.- Variation of c_l and $c_{m_{a.c}}$ with α_o for NACA 6-H-15 airfoil section.

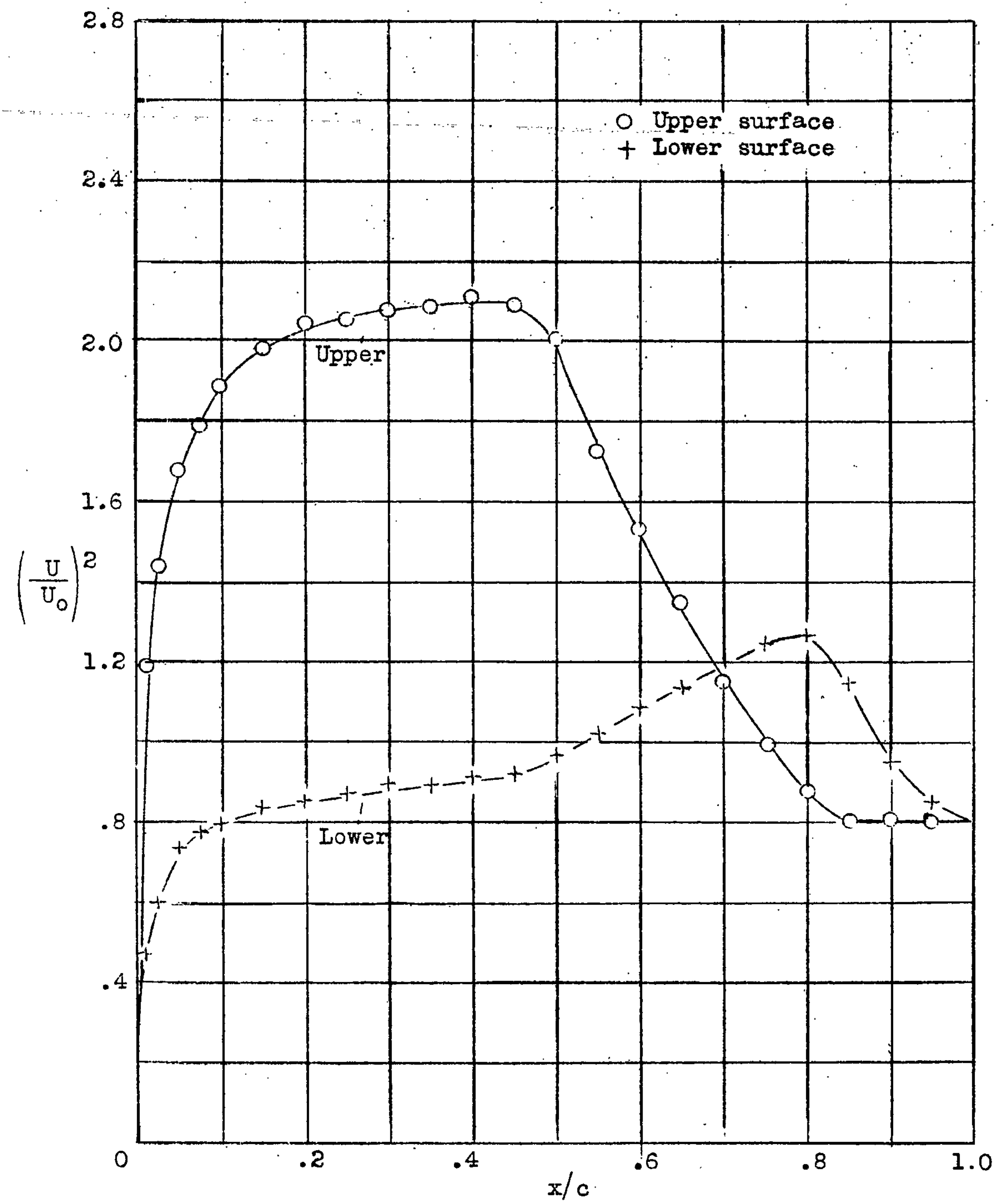

Figure 19.- Pressure distribution on NACA 6-H-15 airfoil section at $c_l = 0.59$. $R = 2.58 \times 10^6$.

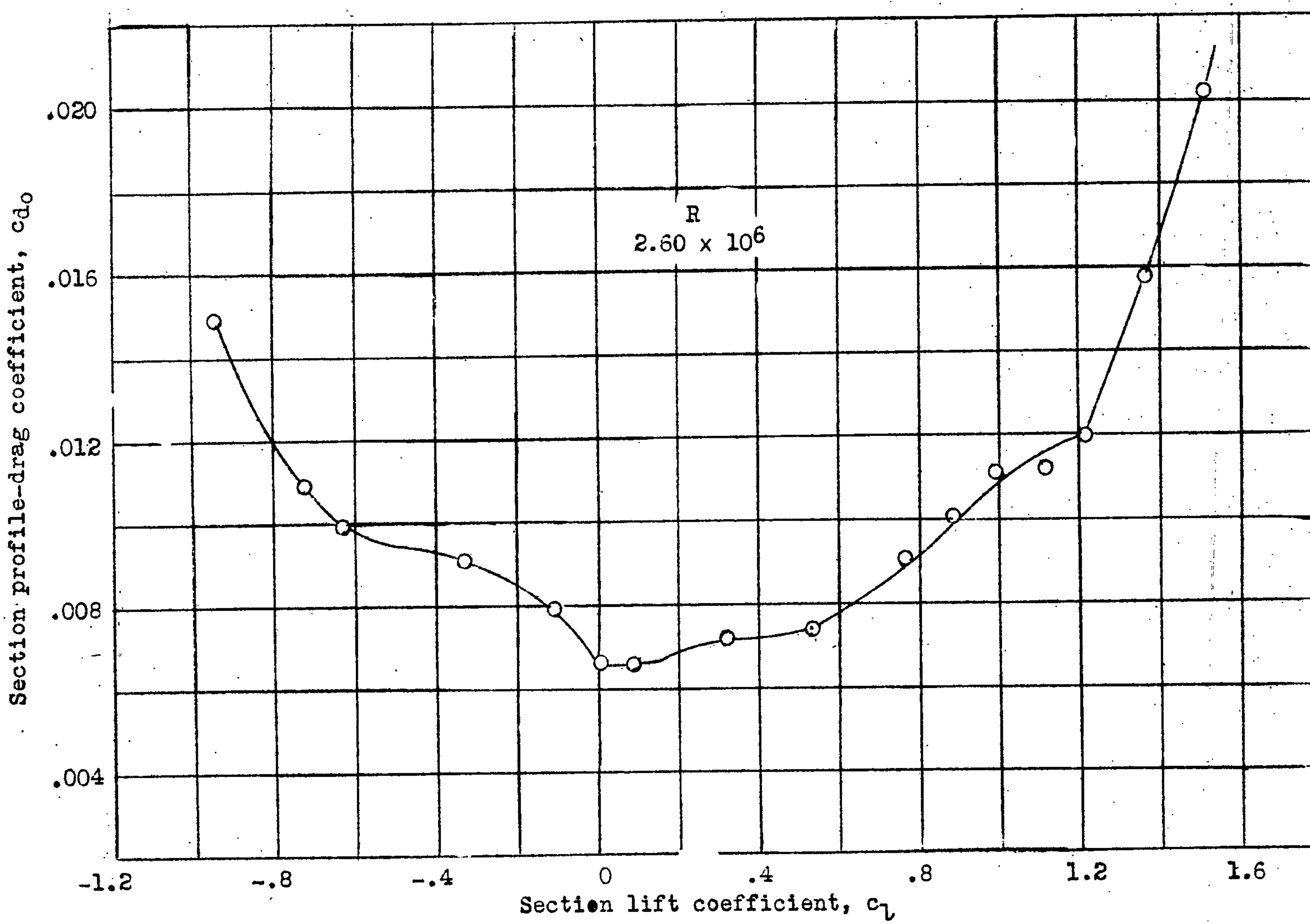

Figure 20.- Lift-drag polar for NACA 23015 airfoil section.

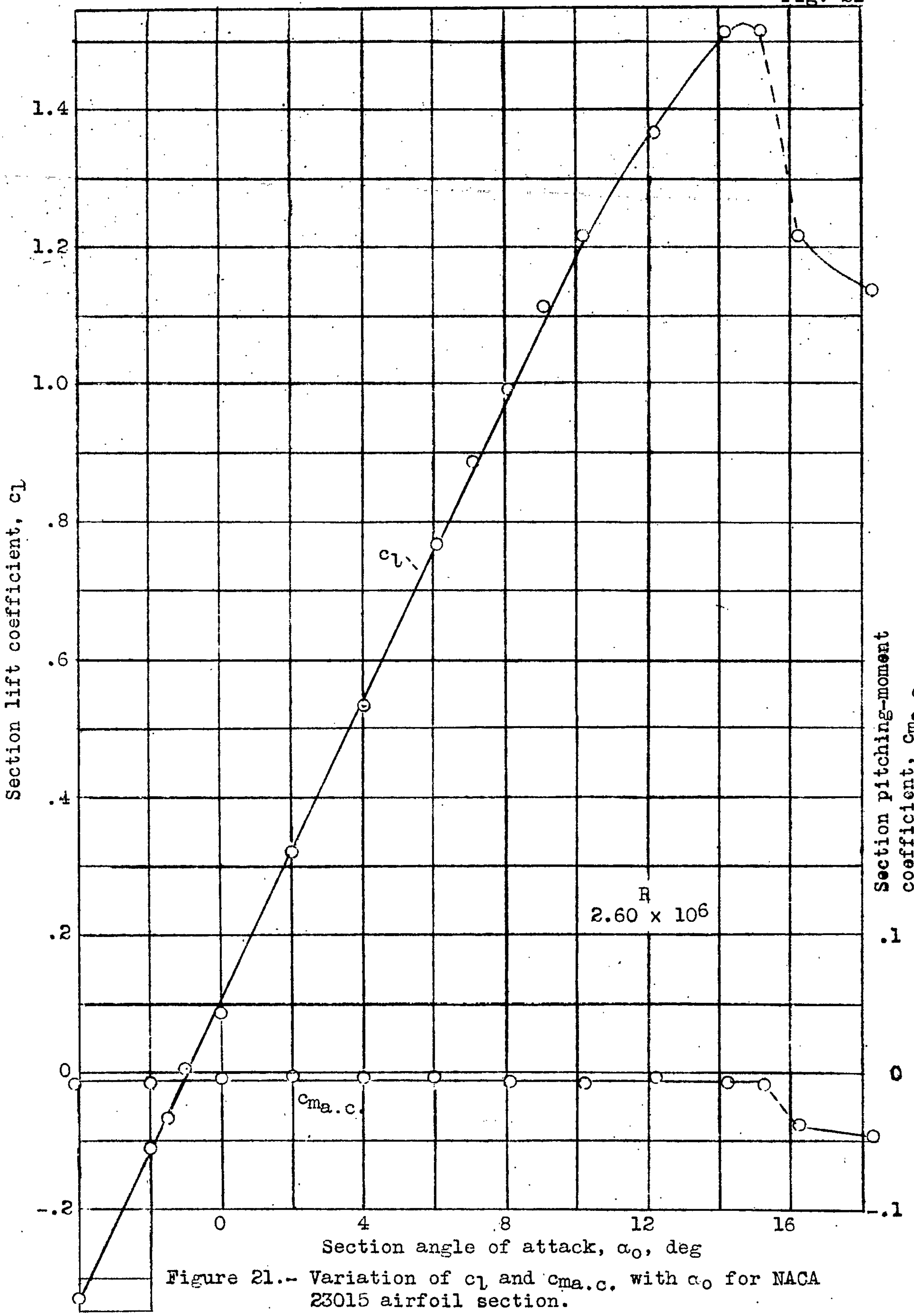

Figure 21.- Variation of c_l and $c_{m_{a.c.}}$ with α_o for NACA 23015 airfoil section.

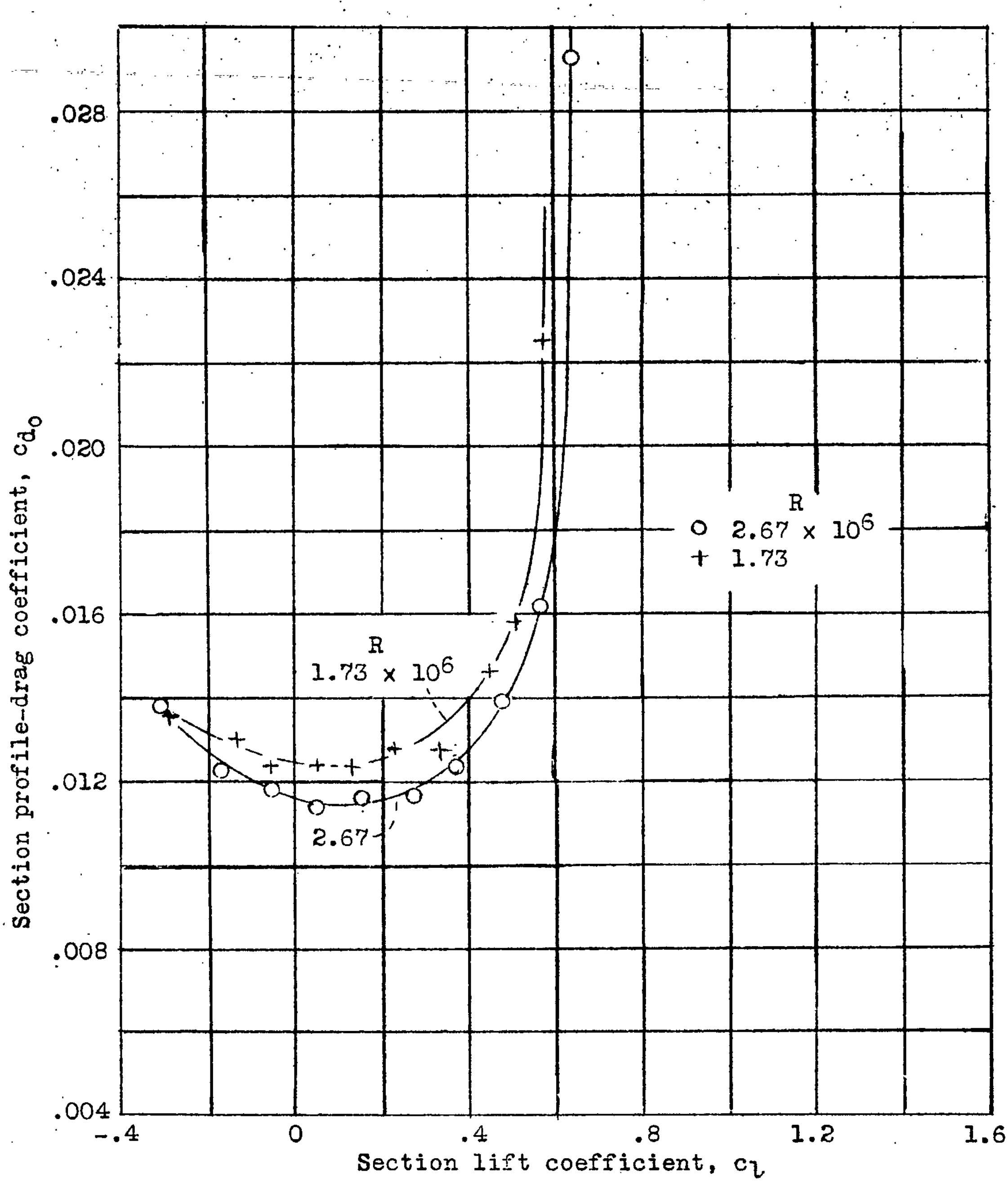

Figure 22.- Lift-drag polar for NACA 5-H-15 airfoil section; airfoil nose roughened.

CONCLUDING REMARKS

New airfoil sections that have small or zero pitching-moment coefficients and high lift-drag ratios have been developed and tested. With sections having pitching-moment coefficients close to zero, maximum section lift-drag ratios that were almost twice as great as those which have been attained on sections of the NACA 230-series airfoils were attained in the Reynolds number range from 1.7×10^6 to 3.2×10^6. The new airfoil sections, because of their small pitching moments and low profile-drag coefficients at moderate lift coefficients, may be suitable for use on the rotor blades of rotating-wing aircraft. It is desirable, however, that some of these sections be tested on a full-scale rotor to observe their characteristics in actual rotor use and to determine whether certain undesirable characteristics, such as sensitivity to surface roughness and change in pitching moment, which were noticed in the tunnel, have a serious effect when the sections are applied to rotor blades.

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2. Jacobs, Eastman N., Abbott, Ira H., and Davidson, Milton: Investigation of Extreme Leading-Edge Roughness on Thick Low-Drag Airfoils to Indicate Those Critical to Separation. NACA C. B., June 1942.